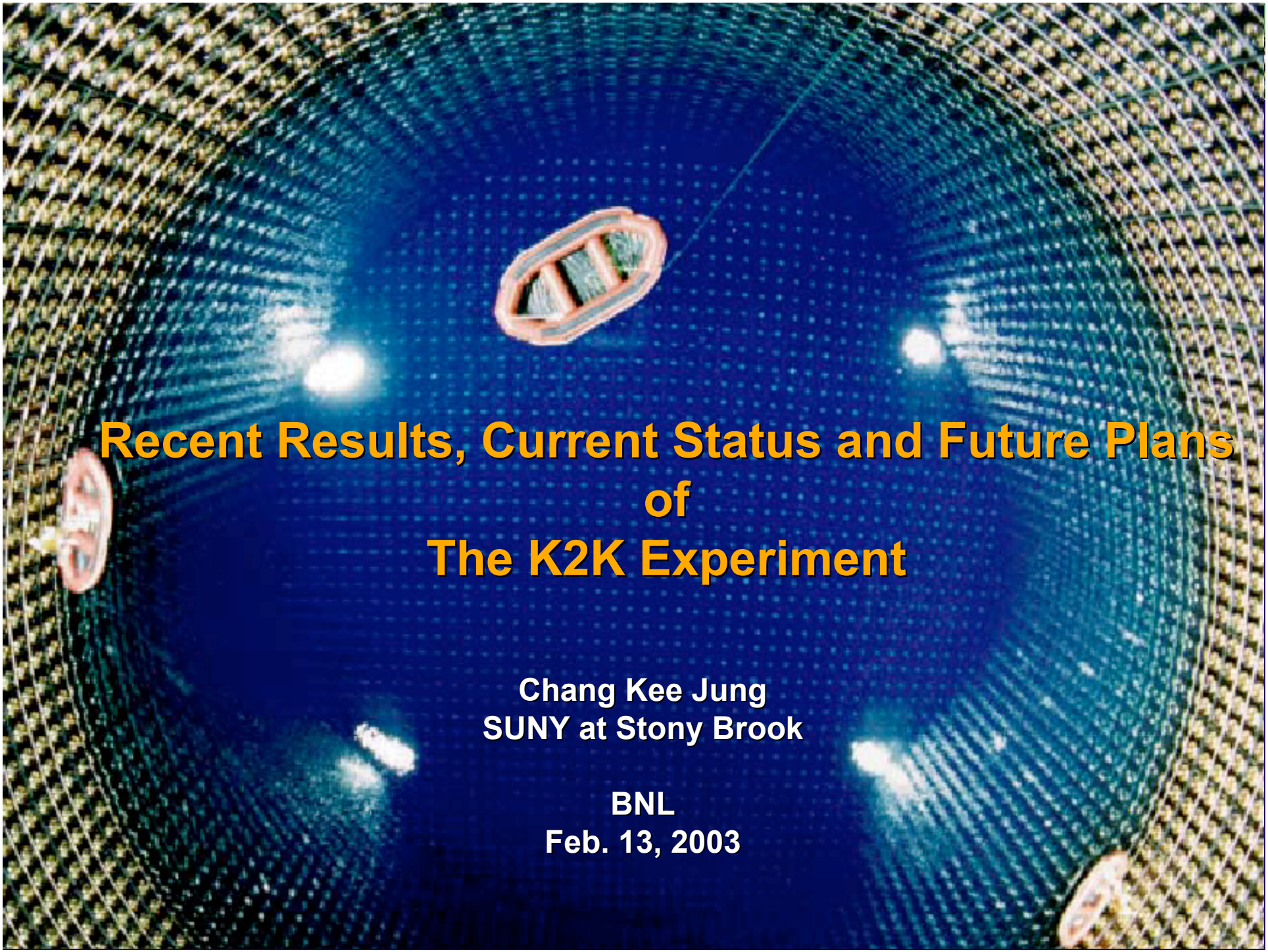

Recent Results, Current Status and Future Plans of The K2K Experiment

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SUNY at Stony Brook

BNL
Feb. 13, 2003

Neutrino Oscillation in Vacuum

weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

mass eigenstates

Survival Probability

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Oscillation Probability

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\Delta m^2 (\equiv m_1^2 - m_2^2)$ *and* $\sin^2(2\theta)$ *are oscillation parameters given by the nature*

L *(source to observer distance) and* E *(neutrino energy) are exerimental parameters*

$$\left(\frac{\Delta m^2 L}{4E}\right) \to \left(1.27\frac{\Delta m^2 L}{E}\right) \quad \text{with} \quad \begin{pmatrix} \Delta m^2 \text{ in } eV^2 \\ L \text{ in } km \\ E \text{ in } GeV \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2 L/E)$$

Lepton Mixing Matrix

$$\vec{\nu}_{weak} = \mathcal{M} \circ \vec{\nu}_{mass}$$

1 Dirac Phase □ CPV

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathcal{M}_{1,e} & \mathcal{M}_{2,e} & \mathcal{M}_{3,e} \\ \mathcal{M}_{1,\mu} & \mathcal{M}_{2,\mu} & \mathcal{M}_{3,\mu} \\ \mathcal{M}_{1,\tau} & \mathcal{M}_{2,\tau} & \mathcal{M}_{3,\tau} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Three Angles

$$\mathcal{M} \longrightarrow \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor analyses}} , \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atm., K2K analyses}} , \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}c^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}c^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{terms probed by future experiments}}$$

If □ is majorana particle, 2 more extra (Majorana) phases
# of extra phases = N □ 1 (w/ N = 3)

Generalized Neutrino Oscillations (for N generations)

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \rightarrow \nu_\alpha + N'$

  is a linear combination of the mass eigenstates ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i} \, |\nu_i\rangle$

- After a distance L (or time t) it evolves $|\nu(t)\rangle = \sum_{i=1}^{n} U_{\alpha i} \, e^{-i E_i t} |\nu_i\rangle$

  it can be detected with flavour β with probability $P_{\alpha\beta} = |\langle\nu_\beta|\nu(t)\rangle|^2$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i}^{n} \mathrm{Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j\neq i} \mathrm{Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin\left(\Delta_{ij}\right)$$

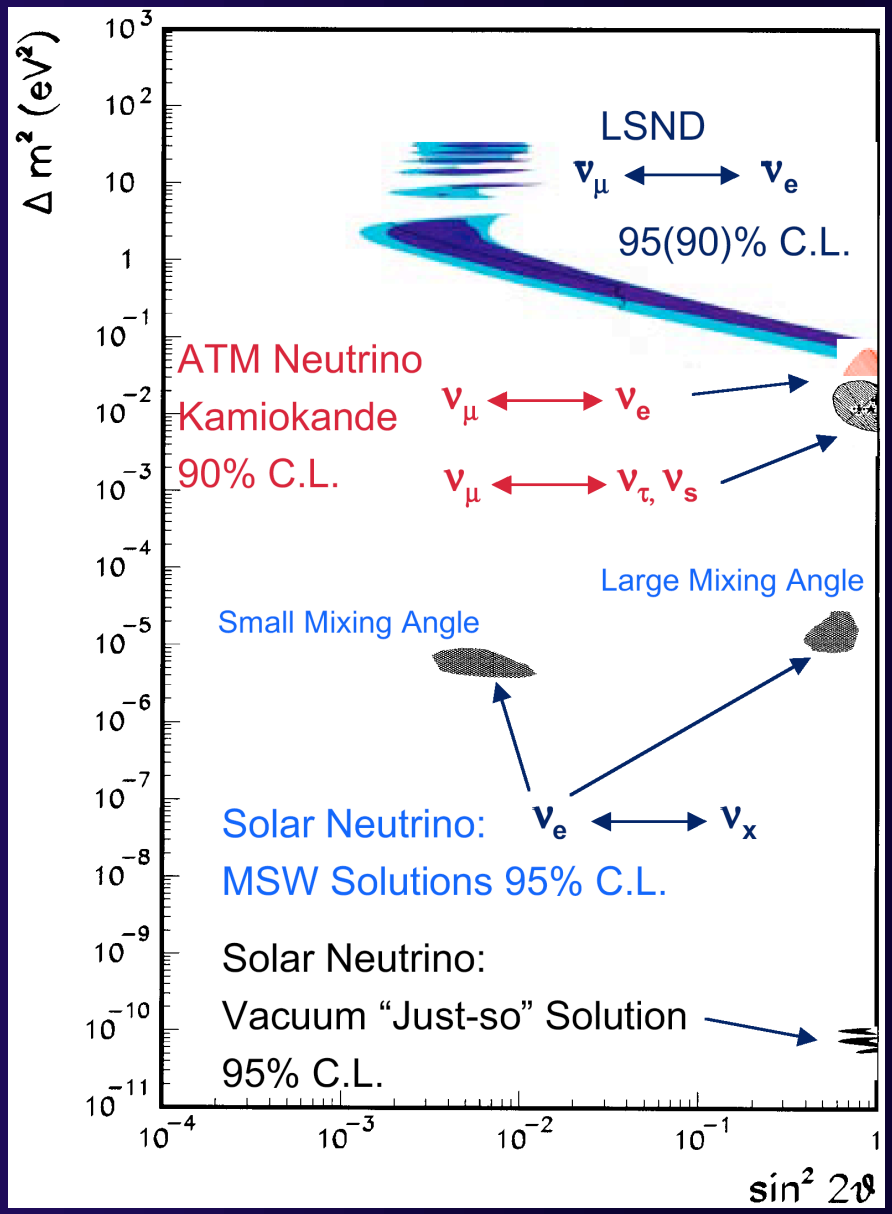
$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

Gonzalez-Garcia

$P_{\alpha\beta} = f(\Delta m^2, U_{\alpha i}, L, E)$, $U_{\alpha i}$: mixing angles + Dirac phases

- **Independent of Majorana phases (cannot be determined by oscillation experiments)**
- **For N=3; 2 independent Δm^2, each with a sign**

Positive Experimental results indicating Neutrino Oscillations (Circa 1996)



3 independent Δm^2 values!!!

$\Rightarrow$ generally requires ν_s

Goals of Neutrino Oscillation Experiments

- Determine # of indept. mass differences sterile neutrinos?
- Measure physical parameters of the oscillation:
  - 3 (6) mixing angles
  - 2 (3) mass differences
  - 2 (3) signs of the mass differences
  - 1 (3) CP violating Dirac phase

  ( ) for 3 active neutrino + 1 additional sterile neutrino
- Observe
  - Oscillatory pattern
  - Wrong flavor appearance
  - matter effect

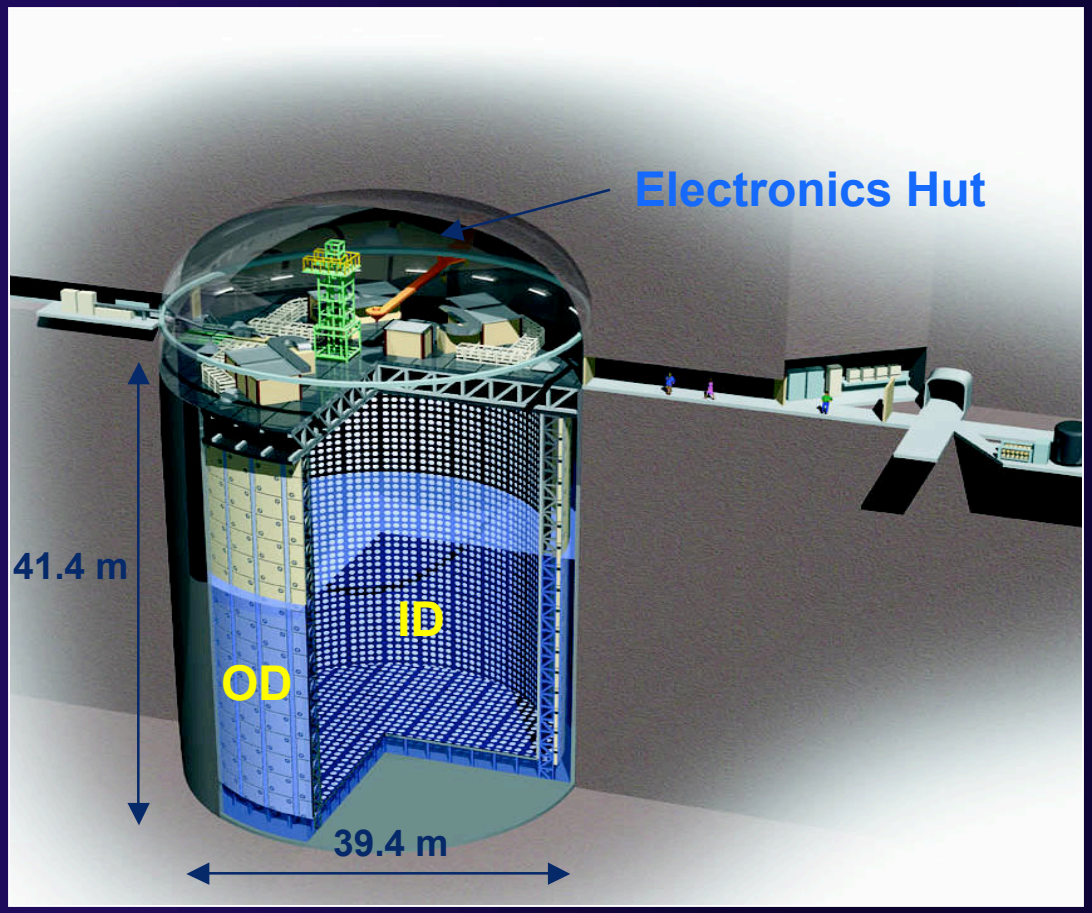
Super-Kamiokande-I Experiment

50 kton Water Cherenkov Detector

-- Inner Detector (ID) w/ 11,000 20” PMTs

-- Outer Detector (OD) w/ 1,840 8” PMTs

-- 40% Photocathode coverage



- Research Goals

Proton decay searches

Solar neutrinos

Atmospheric neutrinos

Astrophysical neutrinos

==> neutrino oscillations

- The Collaboration

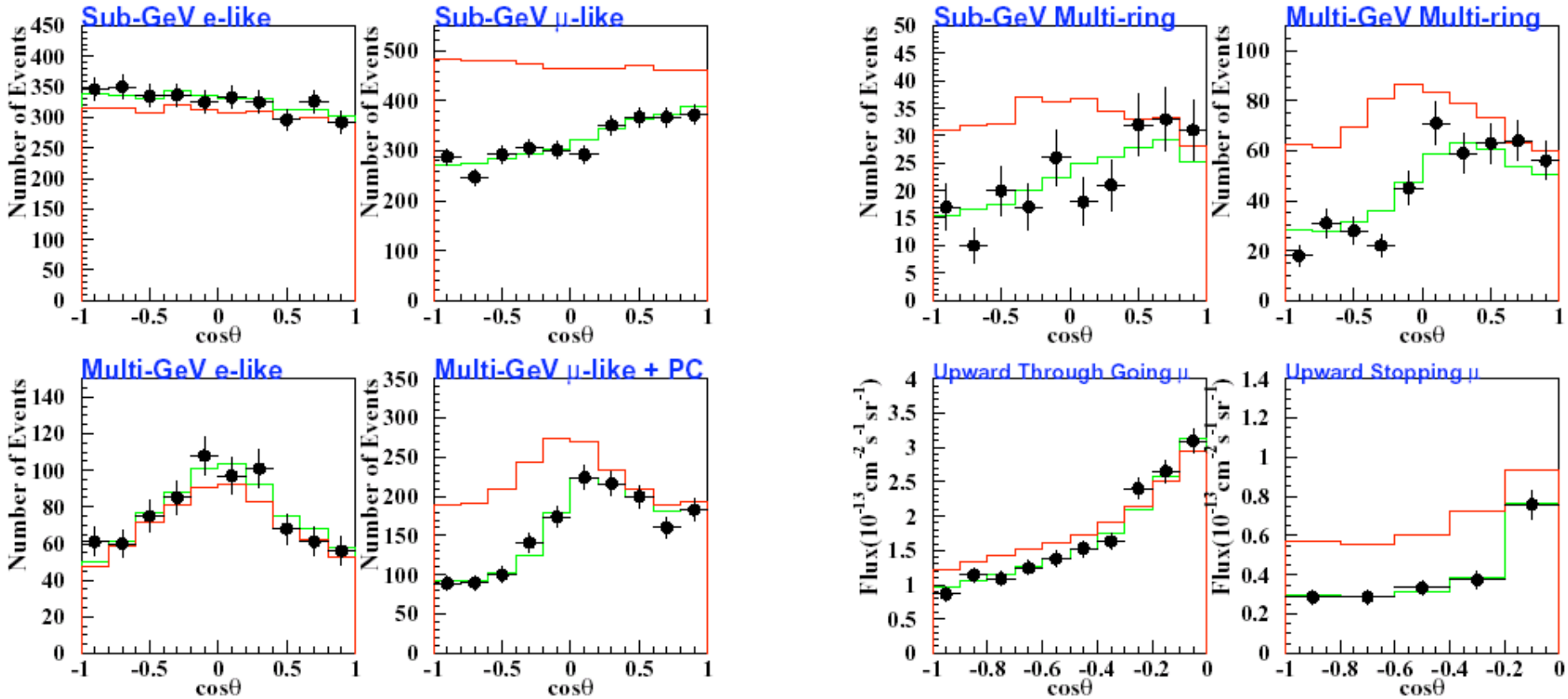
~120 physicists

23 institutions from

Japan and US

SuperK Observation of Neutrino Oscillations

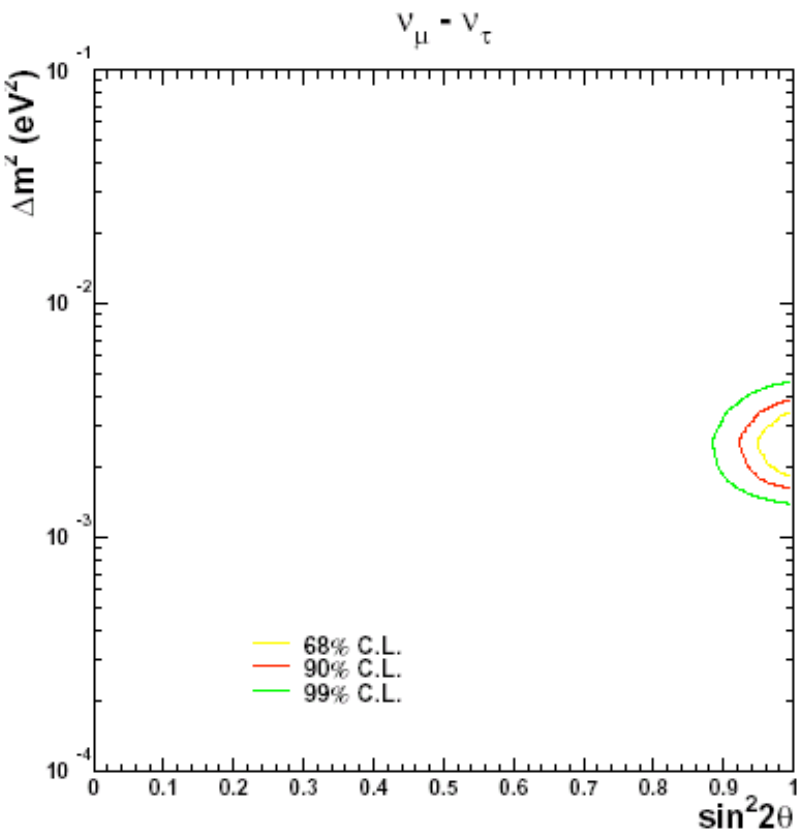
All Super-Kamiokande-I Data: 1489 days



- No oscillation MC: ruled out > 15
- Best fit oscillation MC

Super-Kamiokande Combined Fit

- Combined Fit
  - Sub-GeV and Multi-GeV contained +Partially contained + Stopping and Through going Up-□ + Multi-ring



No oscillation

$\chi^2_{min} = 456.5/170$ d.o.f.)

$\nu_\mu \leftrightarrow \nu_\tau$

Best fit:

$\Delta m^2 = 2.5 \times 10^{-3} eV^2$, $\sin^2 2\theta = 1.0$

$\chi^2_{min} = 163.2/170$ d.o.f.)

$\Delta m^2 \in 1.6 \sim 3.9 \times 10^{-3} eV^2$

$\sin^2 2\theta > 0.92$ 90% C.L.

Summary: Atmospheric Neutrinos

- SuperK firmly establishes neutrino oscillation in atmospheric neutrinos
  - $1.6 < \Delta m^2 < 3.9 \times 10^{-3}$ eV^2, $\sin^2 2\theta > 0.92$ @90% C.L.
  - no internal inconsistency
- Supporting evidence from other experiments
  - IMB, Kamiokande, Soudan 2, MACRO
  - No external inconsistency among experiments

 Far-reaching impact on particle, nuclear and astrophysics

  - SuperK oscillation paper: the most cited (> 1000) exp. particle physics paper ahead of the J/psi paper ("November Revolution")

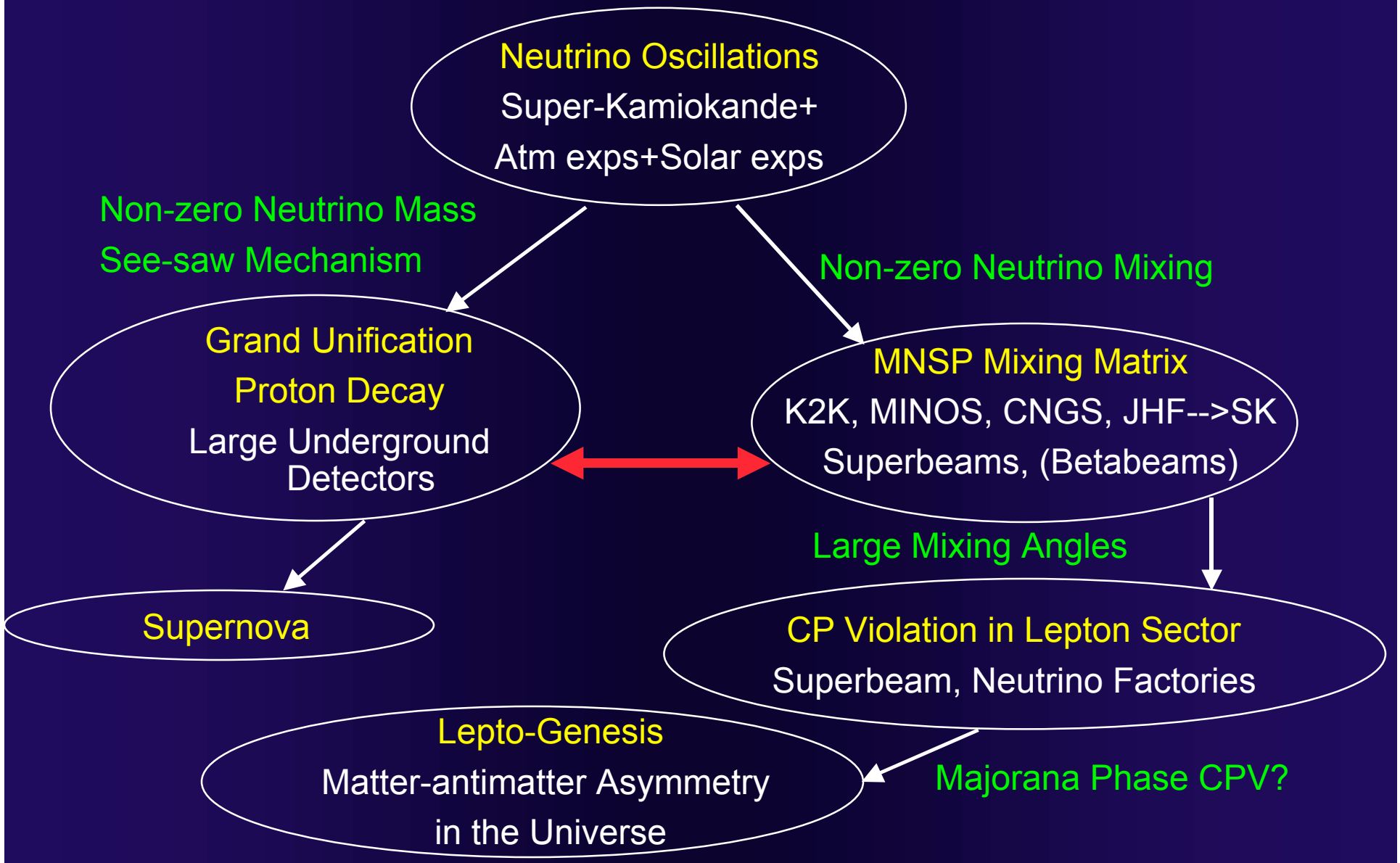
    1 citation/day rate

  - small non-zero neutrino mass (~0.05 eV)

    First experimental evidence for physics beyond Standard Model

    could be the first indication of high energy scale physics (See-saw mechanism) GUT? proton decay?

1998 Neutrino Revolution and Physics Goals for NNN Experiments



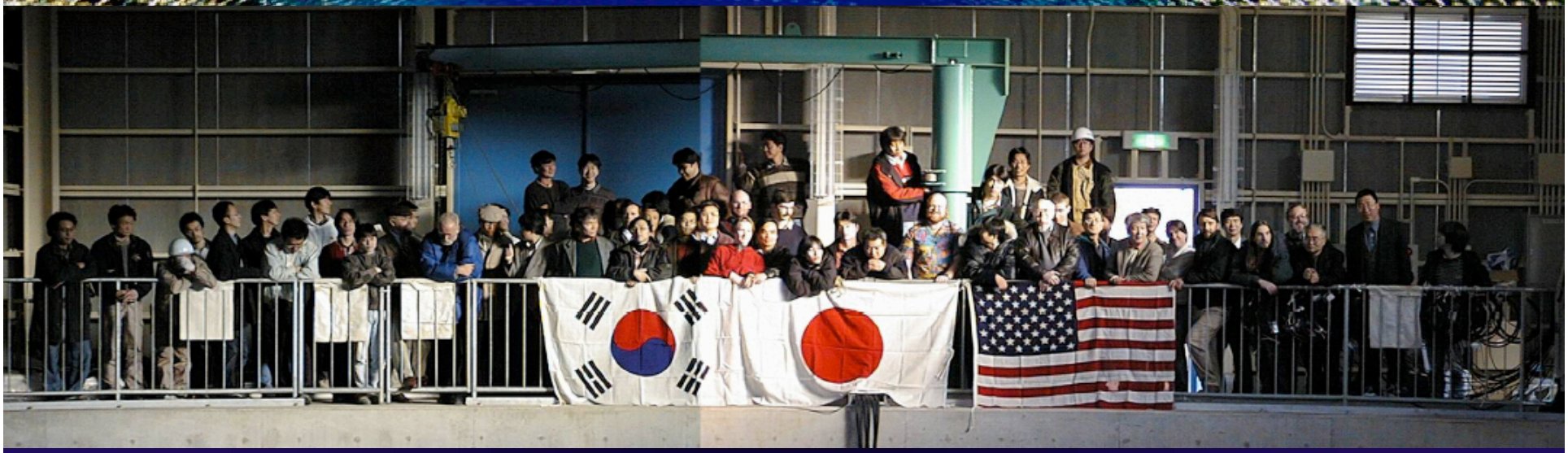
K2K (KEK to Kamioka)

1st Long baseline Neutrino Oscillation Experiment

The Next Step

The K2K Collaboration

(18 institutions from Japan, Korea and U.S. ~100 physicists)



Chonnam National University
Dongshin University
Seoul National University

ICRR, University of Tokyo
KEK
Kobe University
Kyoto University
Niigata University
Okayama University
Osaka University
Science University of Tokyo
Tohoku University

Boston University
University of California, Irvine
University of Hawaii
SUNY at Stony Brook
University of Washington

Warsaw University

K2K Physics Programs

- Neutrino Oscillations
  - confirm SuperK atm neutrino oscillation results
  - muon neutrino disappearance (99% pure ν_μ beam)

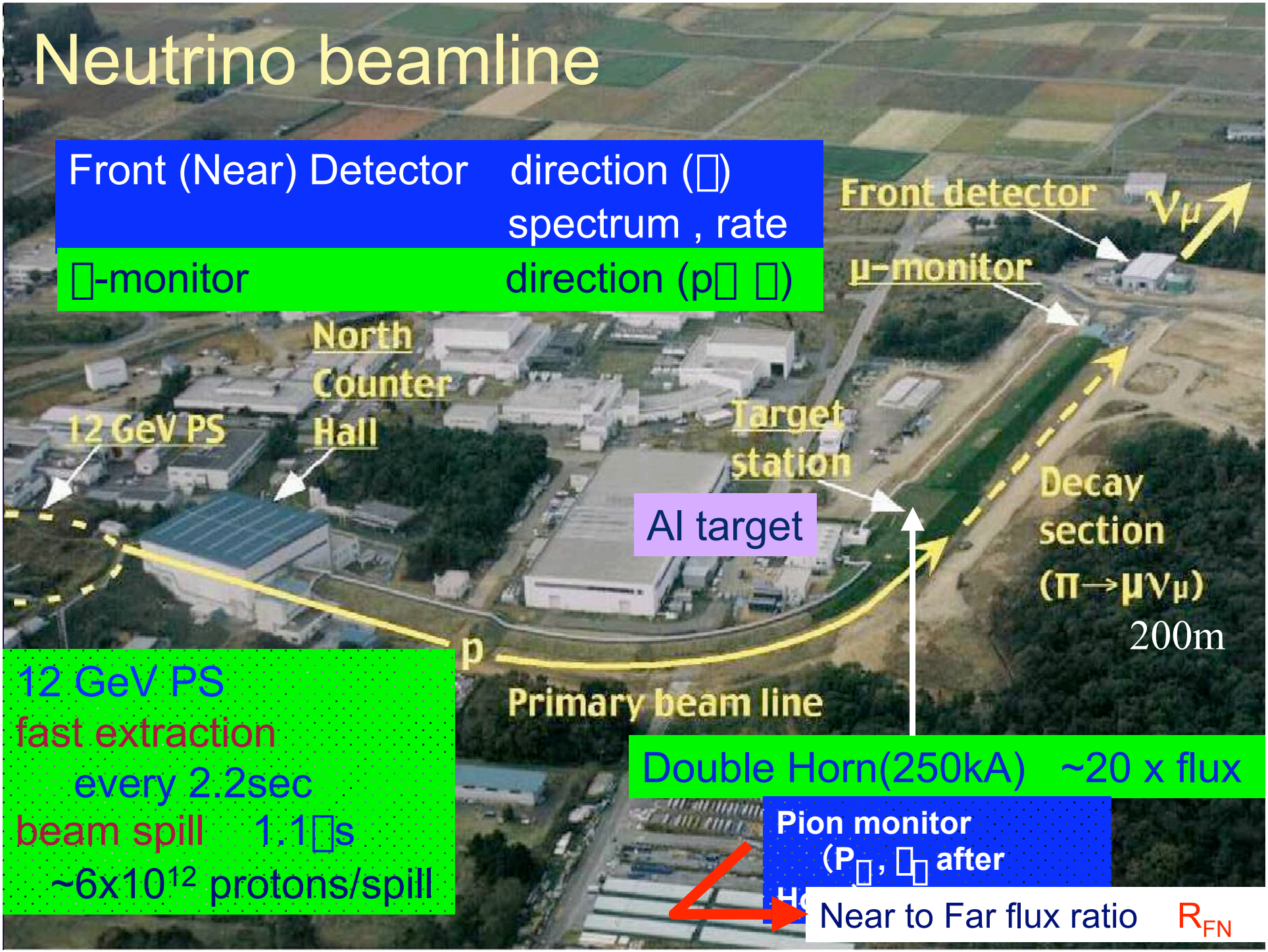
    1) simple counting: observed/expected # of events

    2) distortion in observed energy spectrum

    → direct observation of energy dependent neutrino oscillation
- Neutrino Cross-section Measurements
  - NC π^0 production cross-section

    → application to $\nu_\mu \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_s$ discrimination in SuperK atmospheric neutrino analysis
- Study of Neutrino Background to Proton Decay Searches

Neutrino beamline



Front (Near) Detector	direction (□) spectrum , rate
□-monitor	direction (p□ □)

Al target

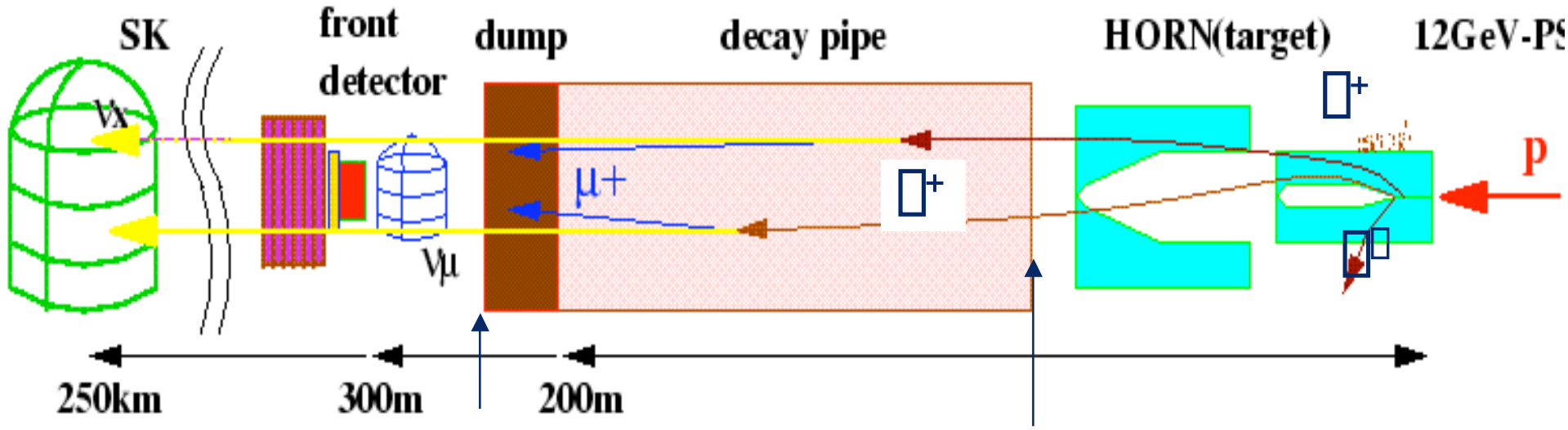
12 GeV PS
fast extraction
every 2.2sec
beam spill 1.1□s
~6×10^{12} protons/spill

Double Horn(250kA) ~20 x flux

Pion monitor
($P_{\square}$, $\square_{\square}$ after

Near to Far flux ratio R_{FN}

K2K Neutrino Beamline

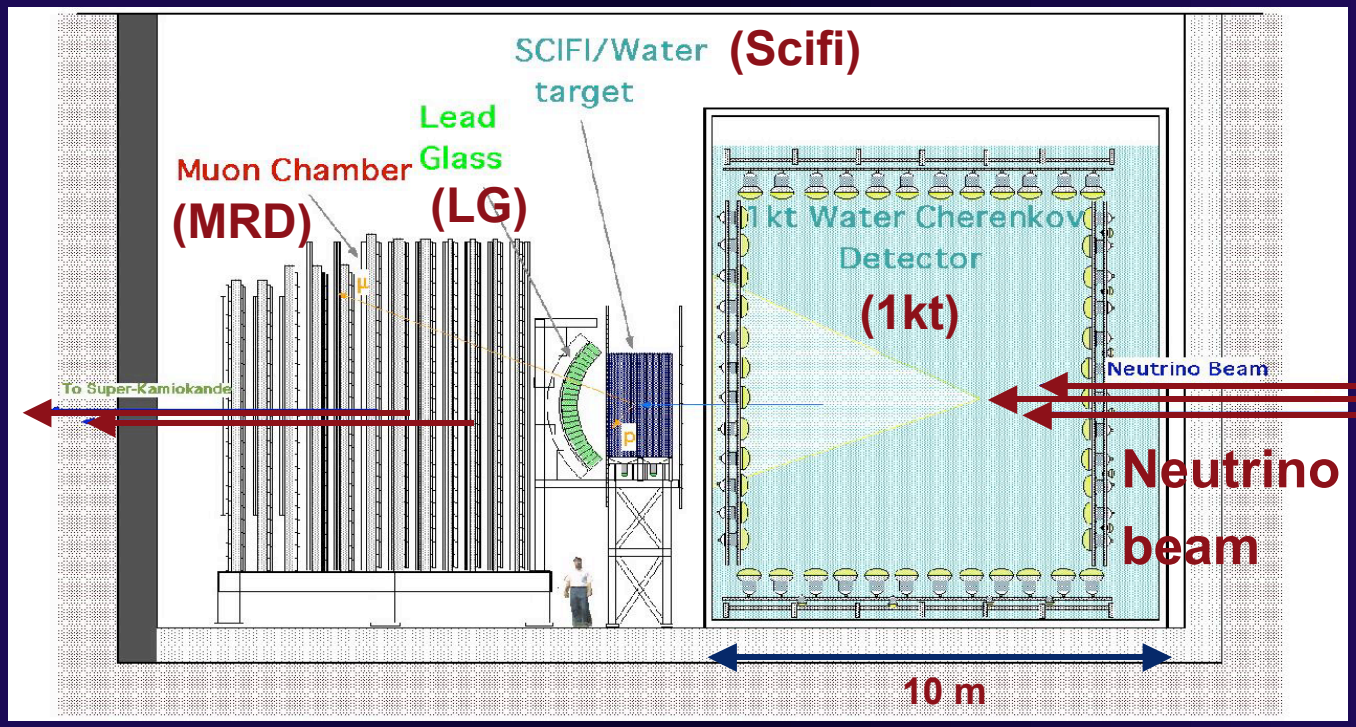


Muon Profile Monitors

Beam Monitors: pion, proton

K2K Near Detector Complex

- 1kt (mini-SuperK): similar systematics as SuperK
- Scifi (scintillating fiber tracker): 19 layers of 6 cm thick water target w/ 20 layers of scifi (x,y), precision tracking
- LG (Lead Glass calorimeter): Measure ν_e contamination
- MRD (muon range detector): 12 layers of iron plates w/ D.C.s

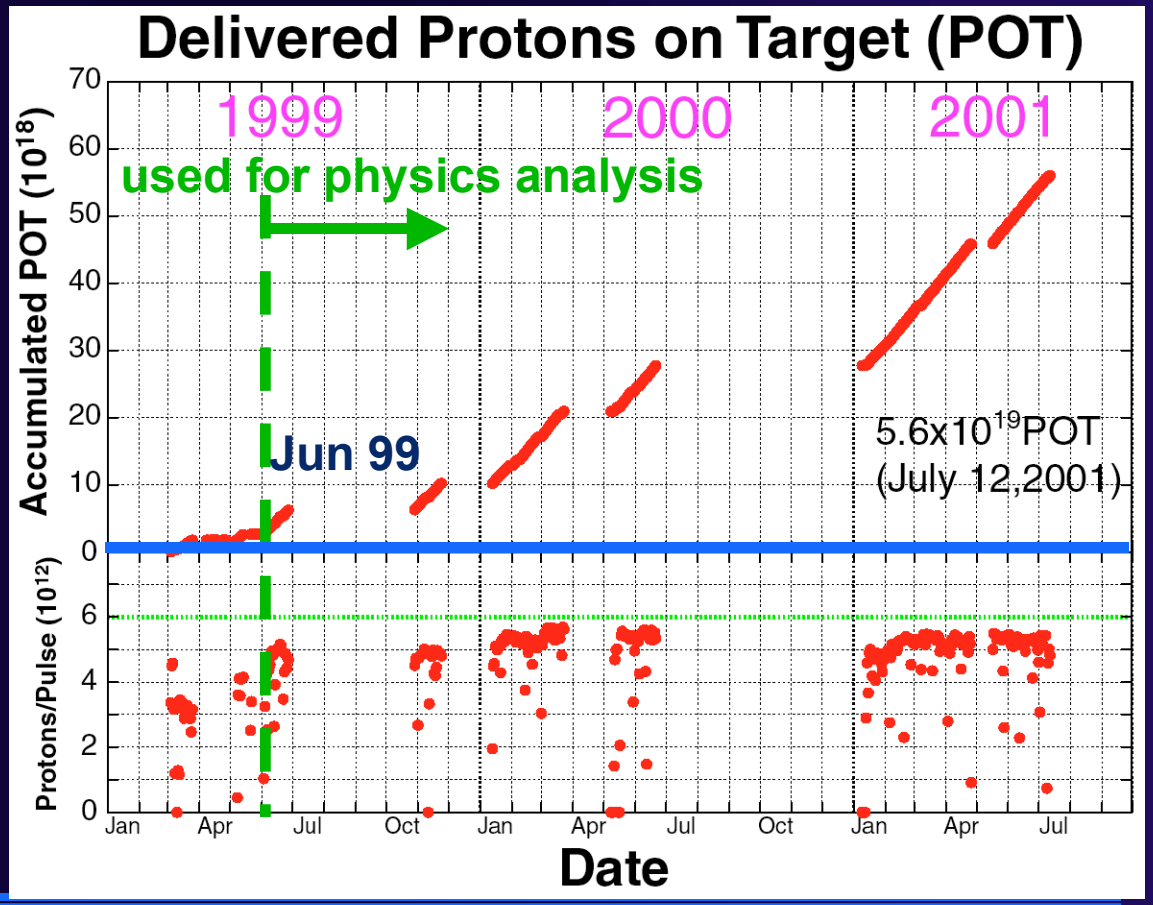


KEK 12 GeV PS - Neutrino Beam

Beam intensity:	~5.5 x 10^{12} protons/pulse
Repetition rate:	1 pulse/2.2 s
Pulse width:	1.1 μs (9 bunches)
Integrated POT delivered:	5.6 x 10^{19} POT (Jul 01)
Average μ beam energy:	1.3 GeV

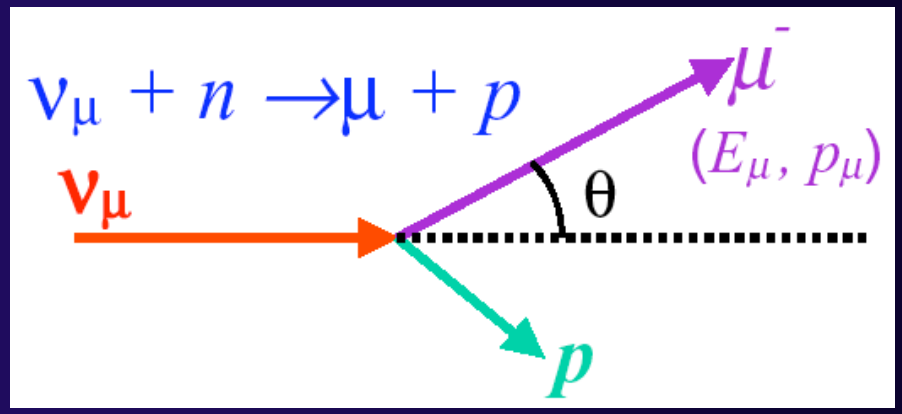
Integrated POT delivered

Beam intensity



K2K Strategy for Observation of Neutrino Oscillation

1. Monitor the Beam Direction
   - muon monitor: spill by spill ($E_{\square}$ > 5GeV)
   - MRD: day by day ($E_{\square}$ > 1GeV)
   - 1 kton: day by day ($E_{\square}$ > 0.2GeV)
2. Measure neutrino beam flux and energy spectrum by utilizing CC QE events ($\square_{\square}$ + n $\square\square$> $\square^{\square}$ + p) at near detectors



$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Recoil proton

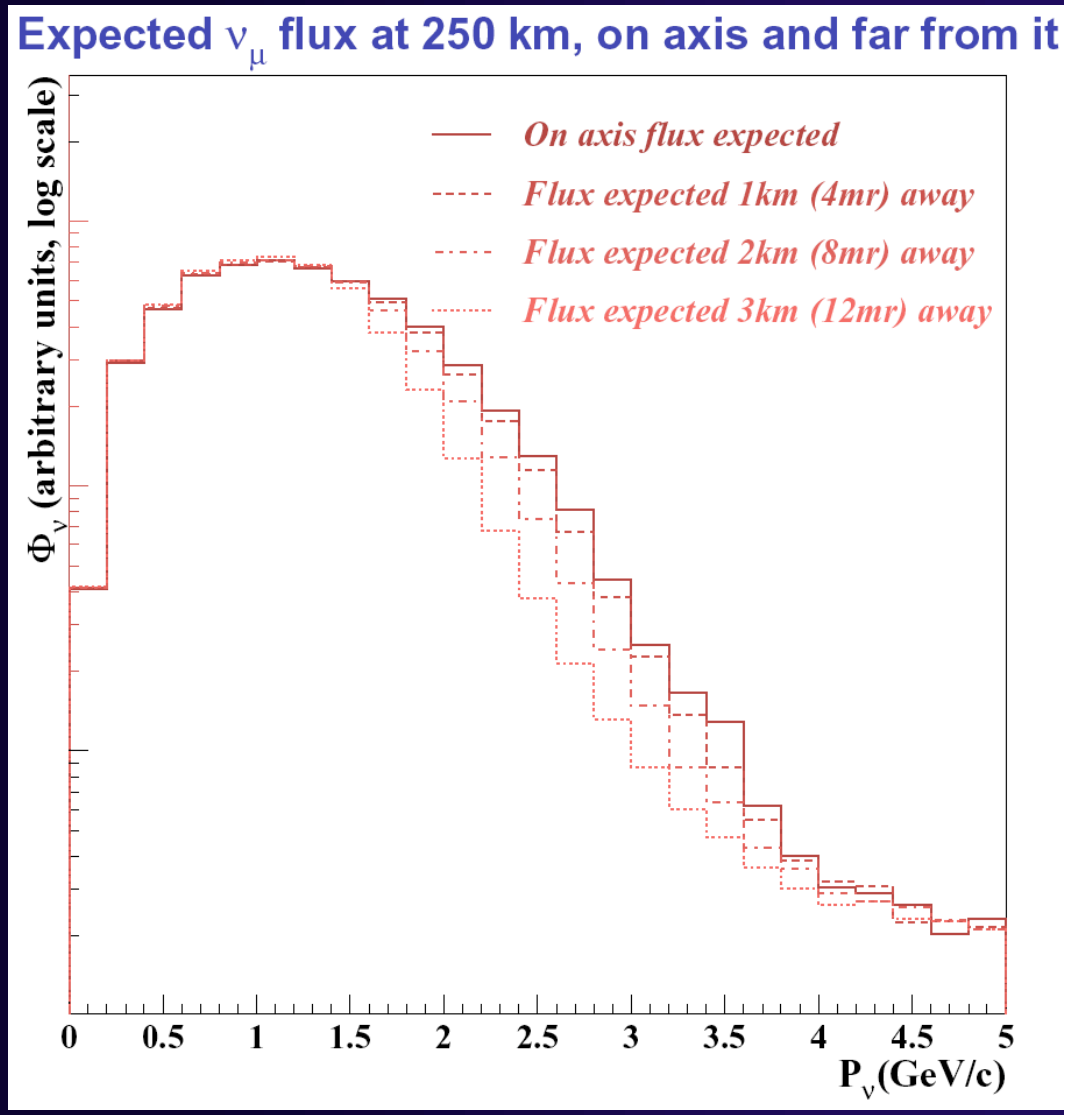
- **not seen in 1kt: below Cherenkov threshold**
- **can be seen in Scifi**

continue: K2K Strategy for Observation of Neutrino Oscillation

3. Extrapolate the measured flux and the energy spectrum with correlated systematic errors at the near detector to the far detector
   - pion monitor
   - beam MC
4. Compare the observed number of events with the predicted and Look for distortion in the measured $E_{\square}$ at SuperK
   - $\square$ fit oscillation parameters

Beam Aiming

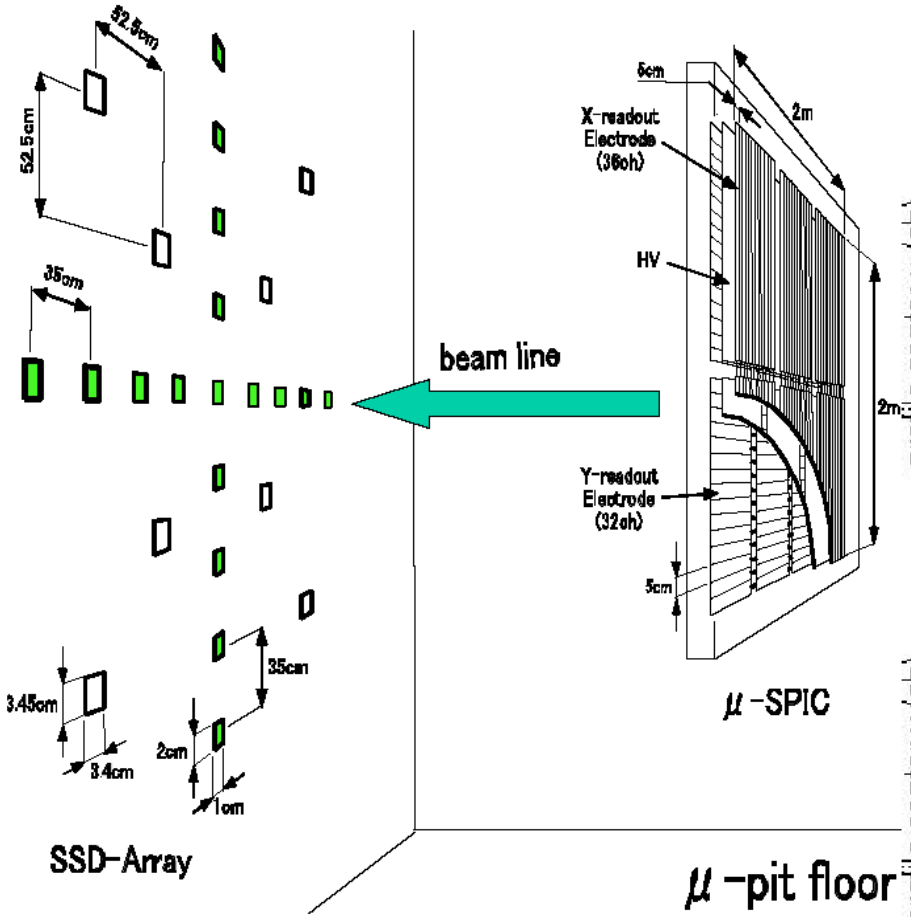
- Survey Accuracy using GPS ~0.01 mrad
- Civil Construction Accuracy ~0.1 mrad
- Beam Aiming Requirement < 3-5 mrad
- Monitored Accuracy < 1 mrad

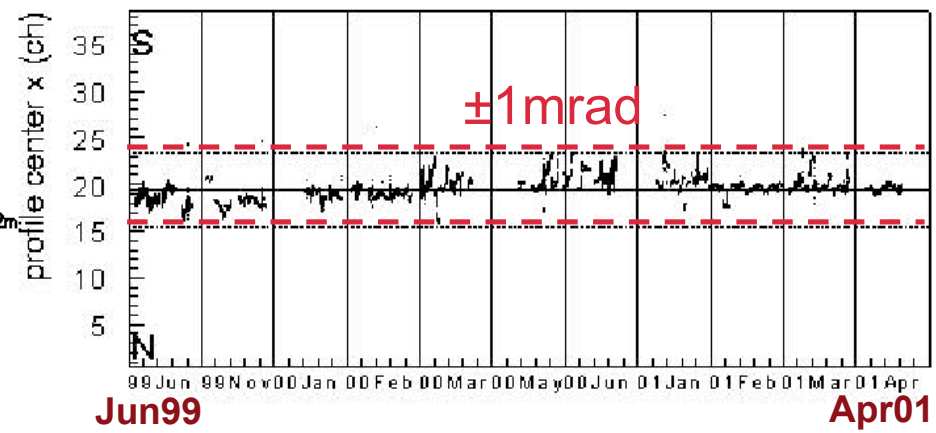


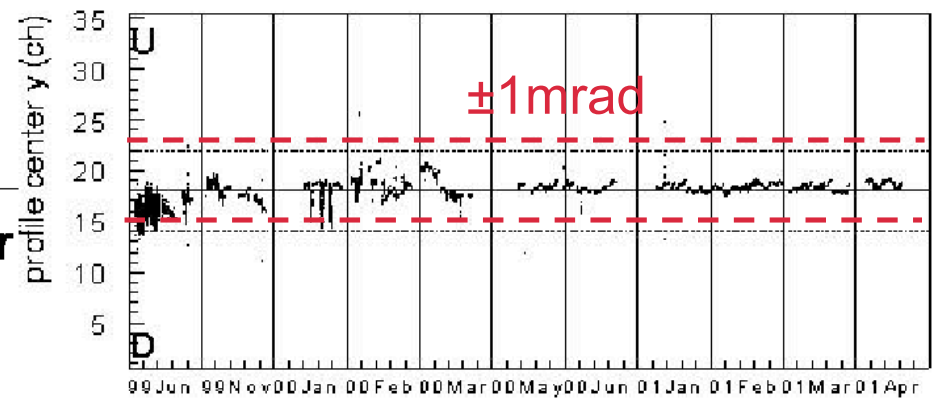
Beam Direction Monitoring: High Energy Muon

Muon monitor

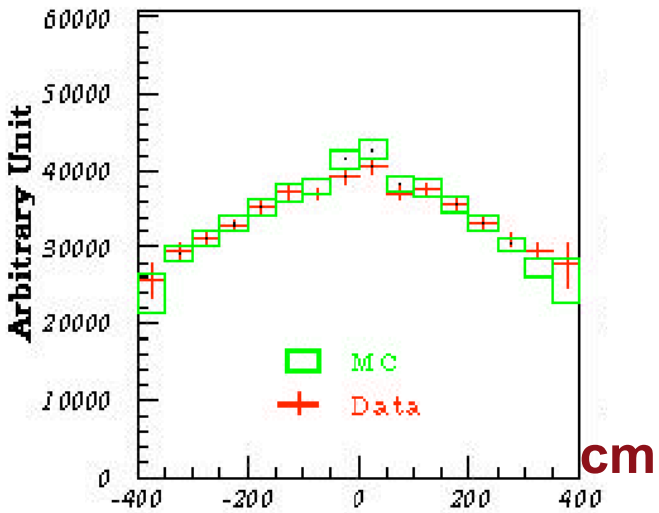
Monitor the profile center of muons **spill by spill.**(at 200 m from the target)



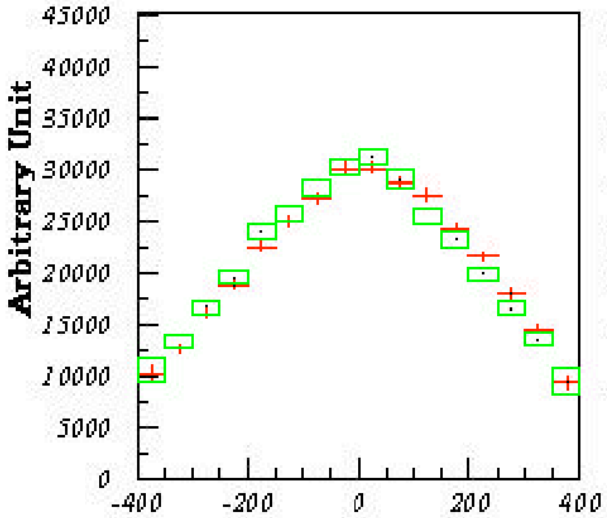




Beam Direction Monitoring: Neutrino

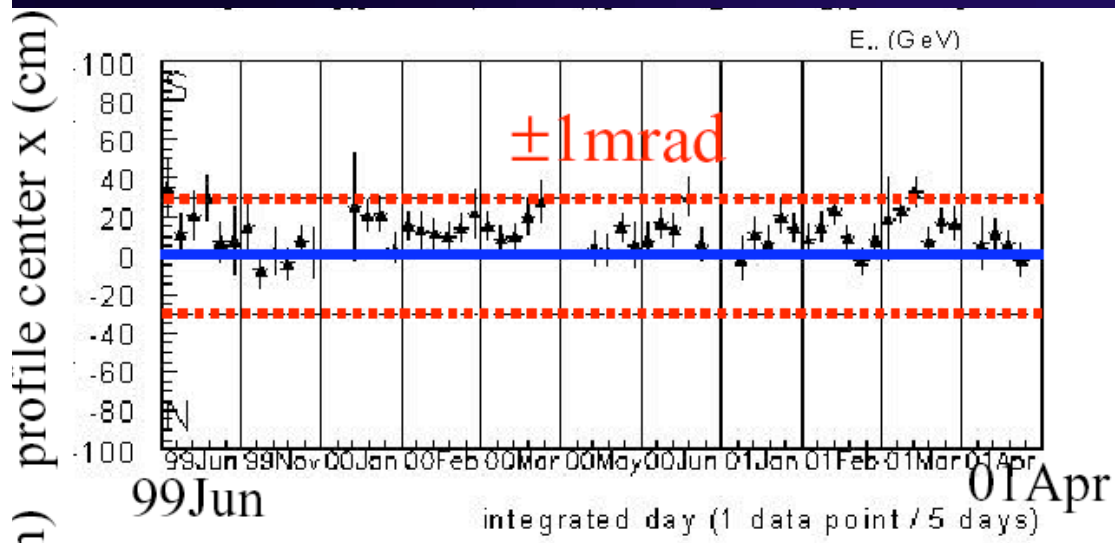


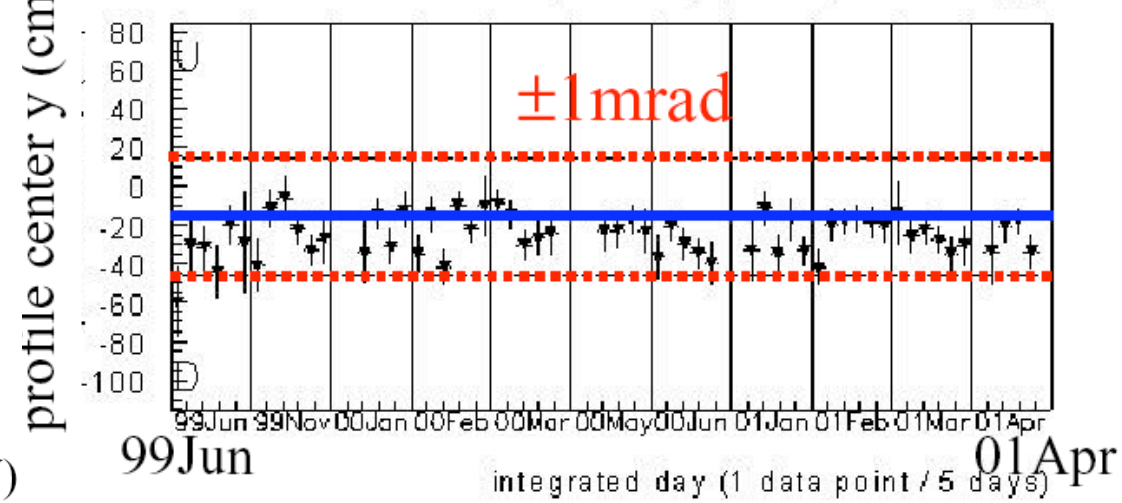
profile x (0.5GeV < E_μ < 1.0GeV)



profile x (1.0GeV < E_μ < 2.5GeV)

Neutrino beam profile center in MRD at 300 m from the target

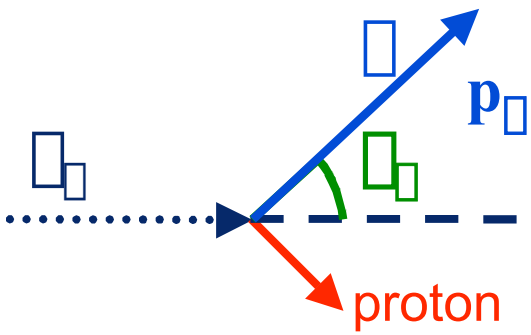




Neutrino interactions around 1GeV

Charged current quasi-elastic scattering (QE)

$E_{\square}$ can be reconstructed from $P_{\square}$ and $\square_{\square}$.



$p_{\square}$: muon momentum

$\square_{\square}$: muon angle

1kt : **single ring □-like FCFV** events

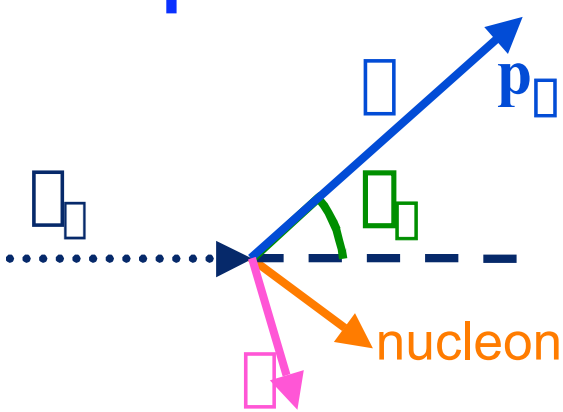
SciFi : **QE-like 2track** events

(when protons are identified)

or single track events

(when protons are not observed)

pion productions

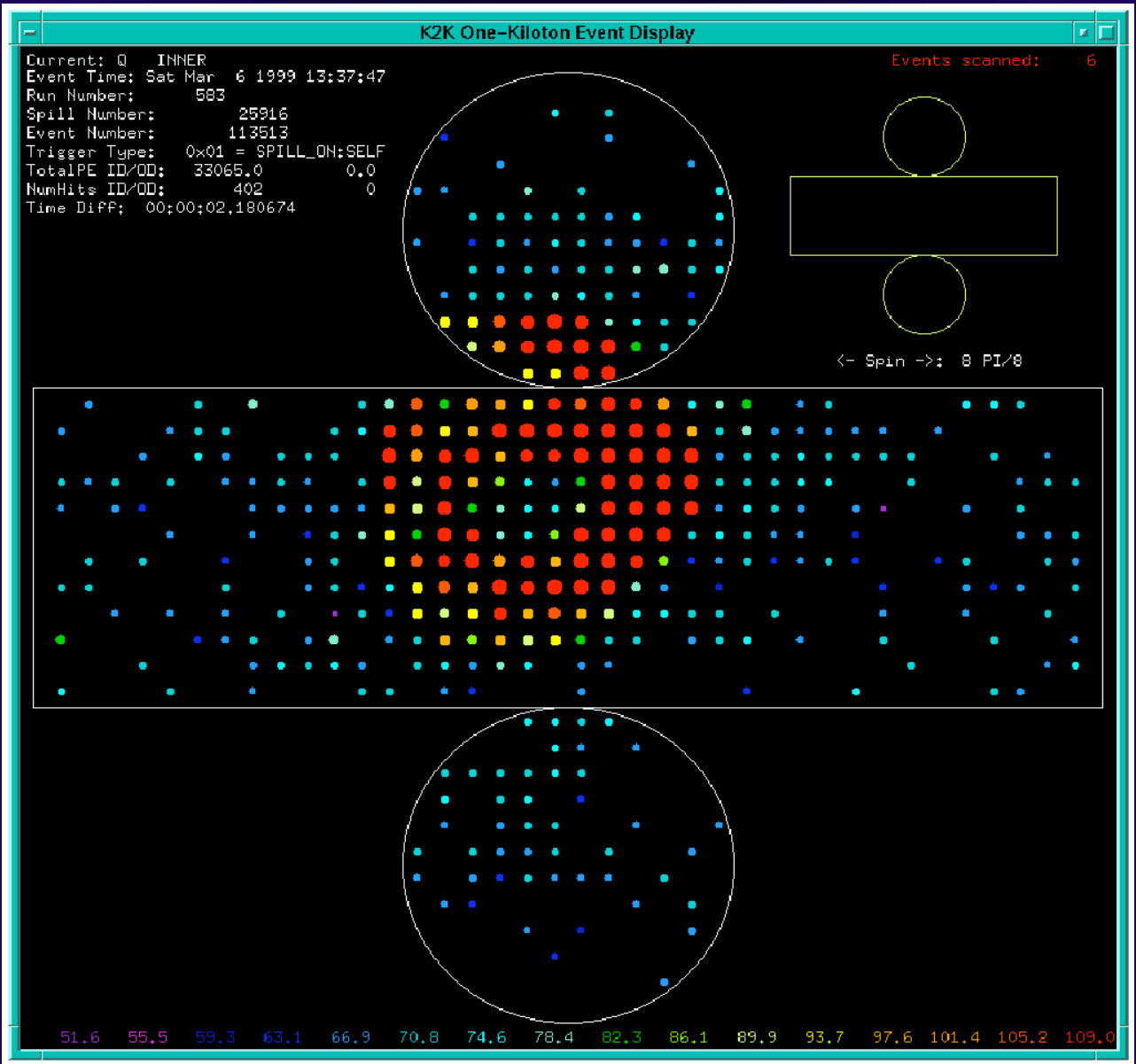


1kt : FCFV events

(single-ring or multi-rings)

SciFi : **non-QE-like** events

Muon-like Event in 1kt

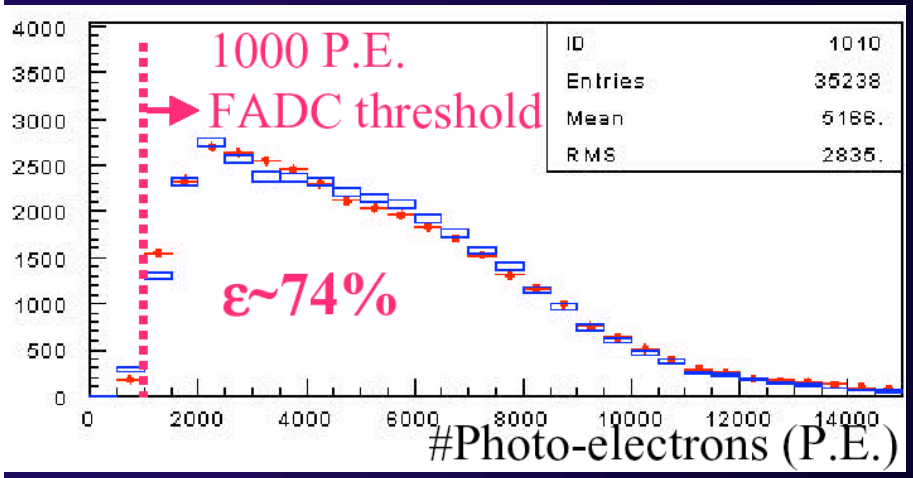


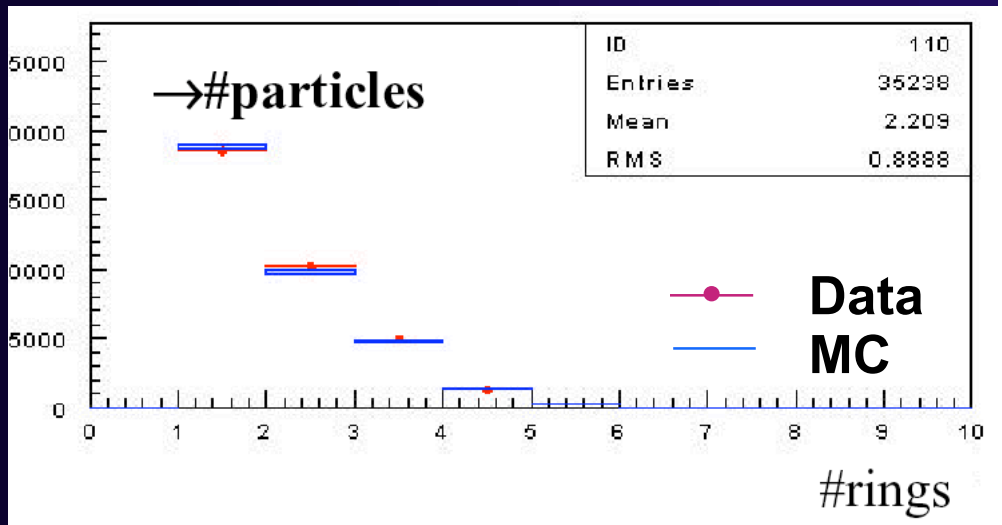
Q

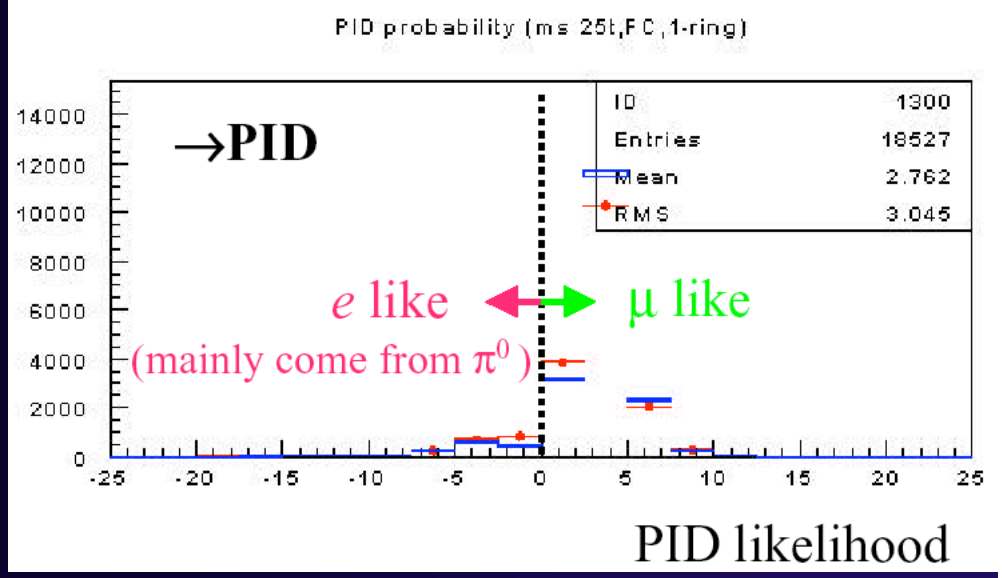
Characteristics of 1kton Events

FC Events

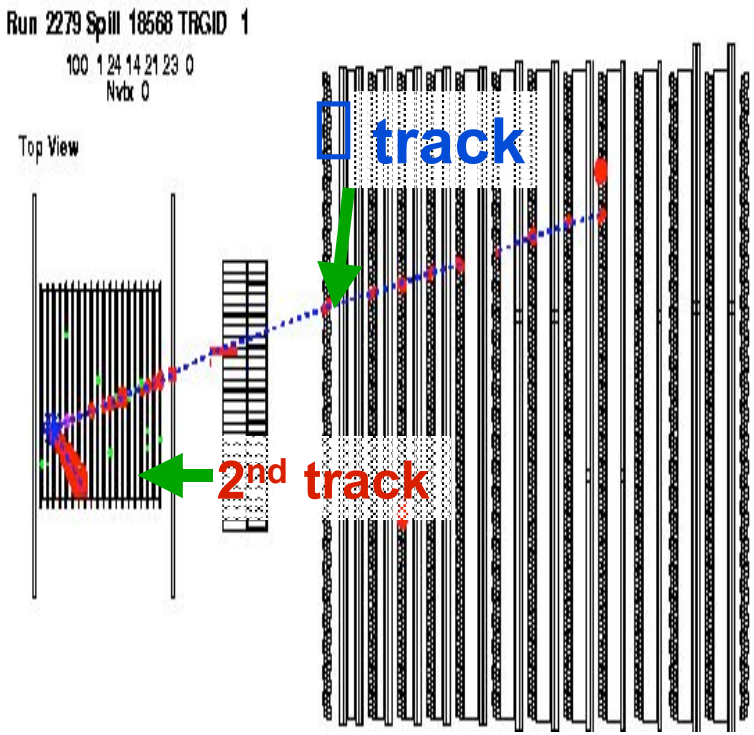
25 ton Fiducial volume (4mϕ×2m)

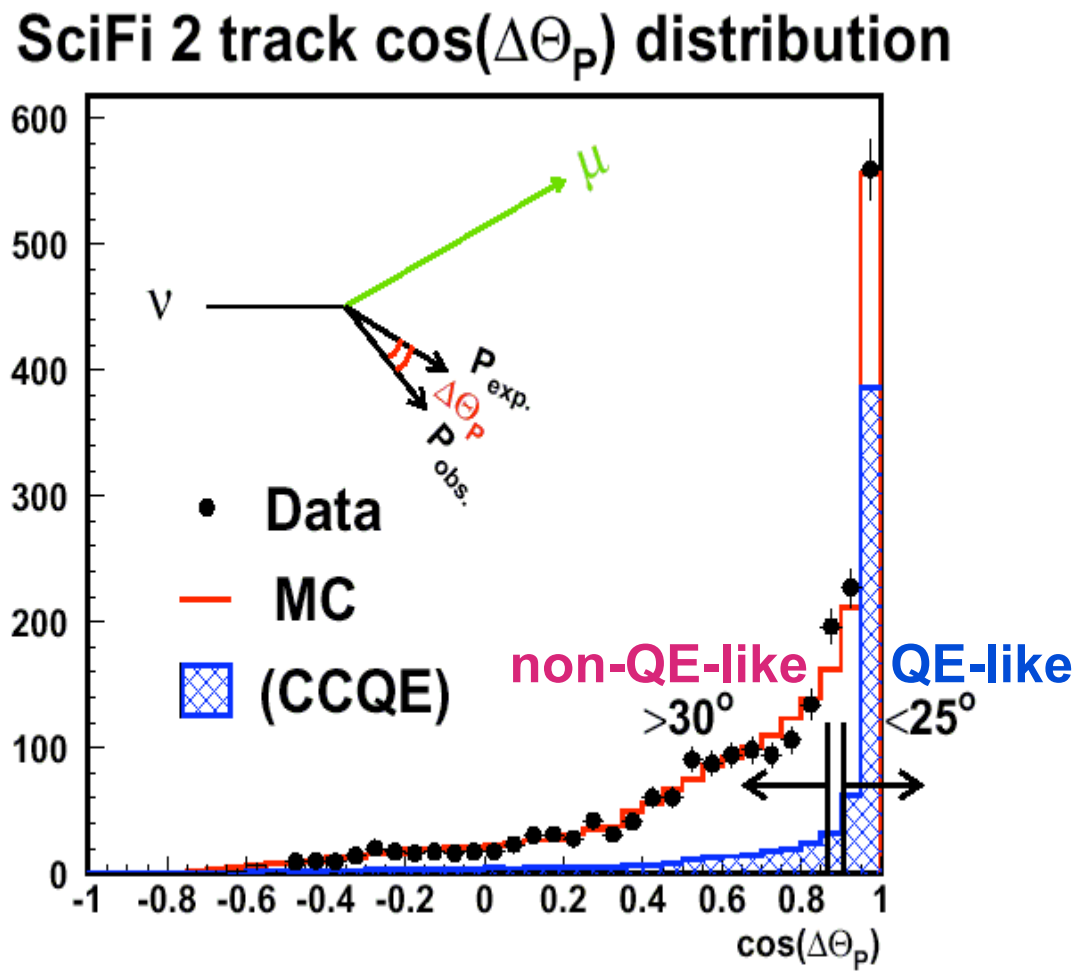






QE and non-QE events in SciFi 2-track events





$\Delta\Theta_p = |\Theta_{exp} - \Theta_{obs}|$

- $\Delta\Theta_p$ < 25 deg. : QE-like
- $\Delta\Theta_p$ > 30 deg. : non-QE-like

Flow of the oscillation analysis

Observed quantities at the near detectors

$(P_{\square}, \square_{\square})$ for each event category

↓ Neutrino interaction models

Obtain neutrino spectrum at near detectors

↓ Near to Far extrapolation $(R_{FN}(E_{\square}))$

Predict neutrino spectrum without oscillation $(\square_{SK}(E_{\square}))$

Observables at SK	• number of events (N_{SK})
	• Reconstructed energy of $\square$ $(E_{\square}^{rec})$

→ Fit the observed results at SK with $(\sin^2 2\square, \square m^2)$

Use maximum likelihood fit

Used data for $\Phi_{near}(E_{\nu})$

KT

Fully Contained Fiducial Volume (FCFV) events

(0) No. of events (Evis >100MeV)

(1) Single μ-like events

SciFi

(2) 1-track μ events

(3) 2-track QE-like events

(4) 2-track non QE-like events

→ 4 sets of (p_{μ}, θ_{μ}) distributions

Pion monitor & Beam simulation

π distribution in (p_{π}, θ_{π})

ν flux estimation $\Phi_{near}(E_{\nu})$ w. error

ν flux $\Phi_{near}(E_{\nu})$ (8 bins)

ν interaction model

(parameterized as QE/non-QE ratio)

Fitting method (□ flux at KEK)

Prepare MC templates

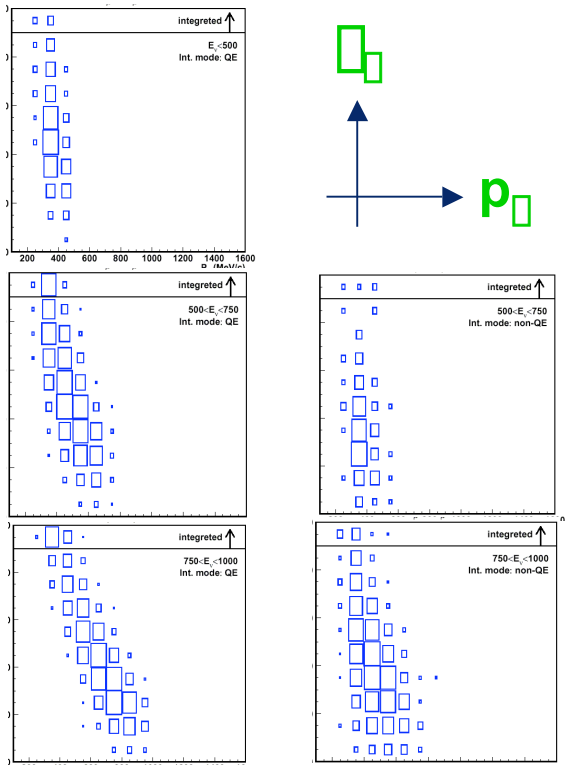
neutrino spectrum □(E□)
and □ interaction model
(QE/non-QE ratio).

E□ QE(MC) non-QE(MC)

0 ~0.5 GeV

0.5 ~0.75GeV

0.75 ~1.0GeV

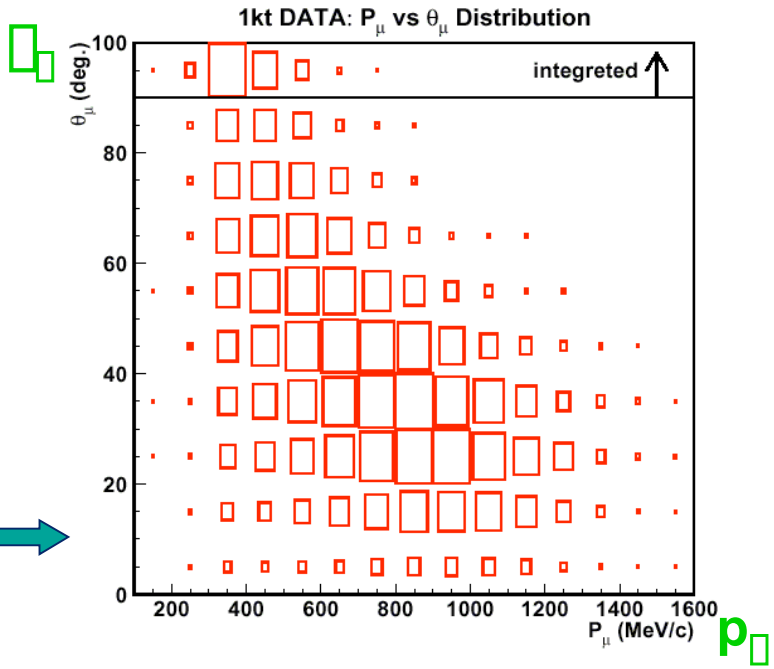


8bins 7bins

□□

p□

Measured (p□, □□)



□□

p□

Fit the parameters.

□(E□) , QE/non-QE ratio …

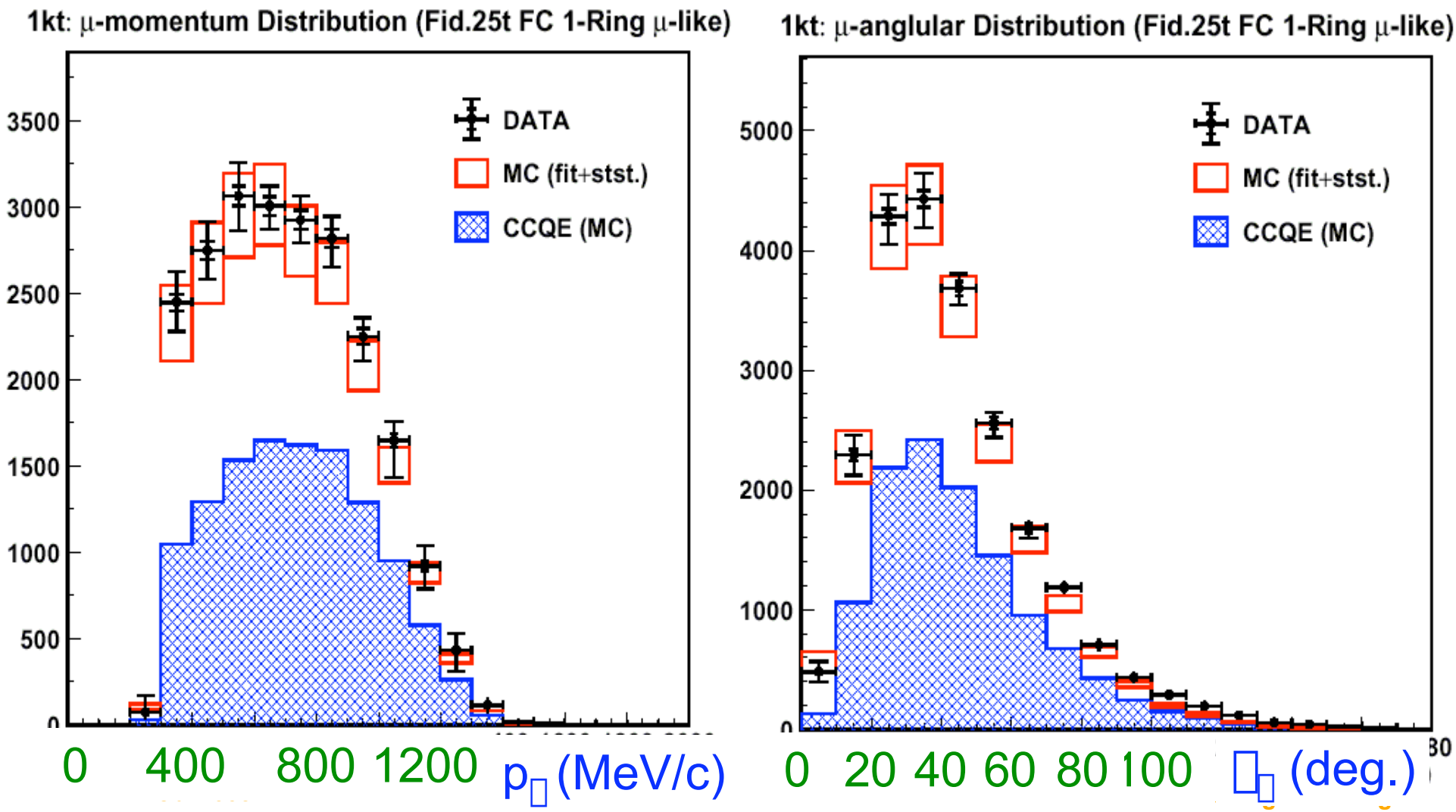
□^{2}=227 for 197 d.o.f.

(90 from 1kt, 137 from FGD)
for fitted (p□, □□) dist. of 1KT
and FGD (124 data points)

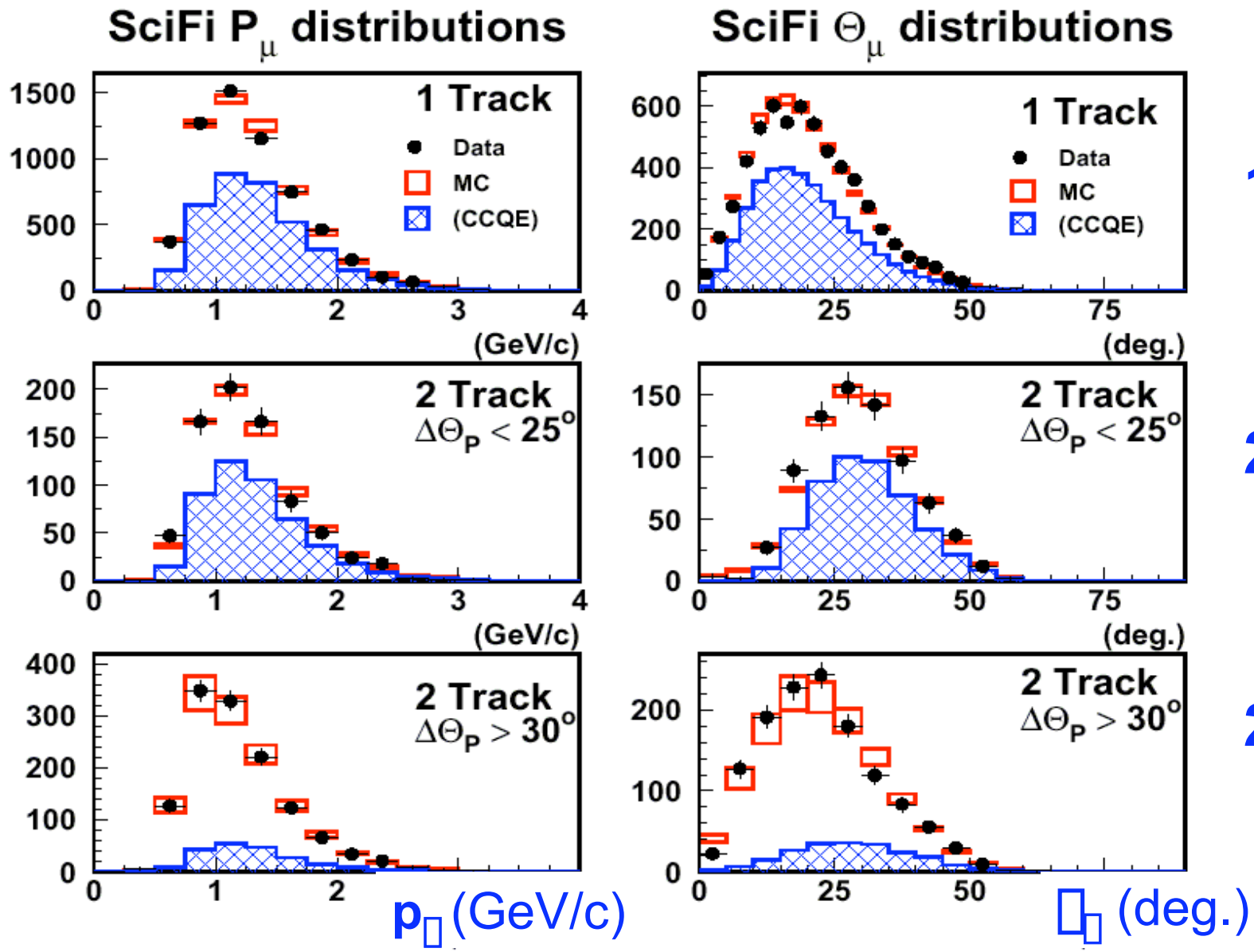
Fitted Results (1kt)

$p_{\square}$ and $\square_{\square}$ distributions of 1kt 1ring $\square$-like FCFV events

Both distributions **agree well** with the fitted MC.



Fitted Results (SciFi)



1track

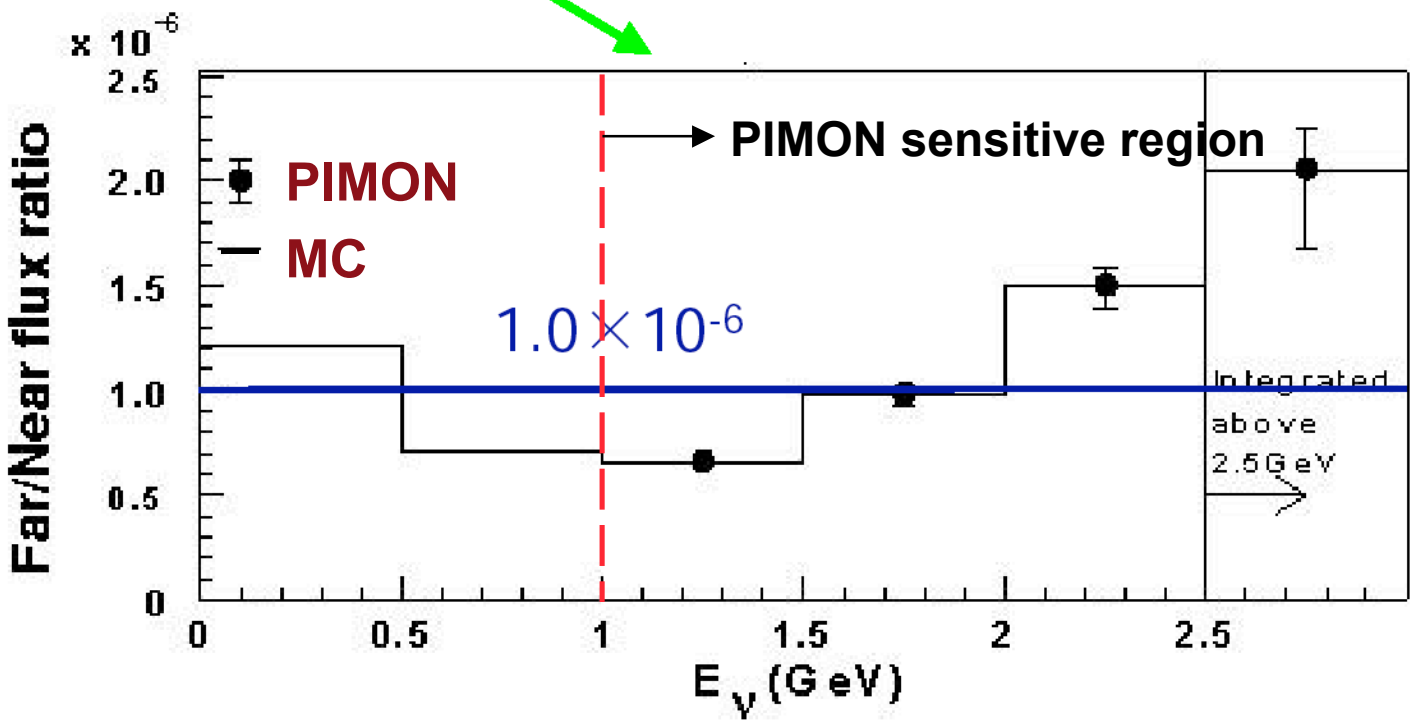
2track
QE like

2track
non-QE
like

Extrapolation to SuperK

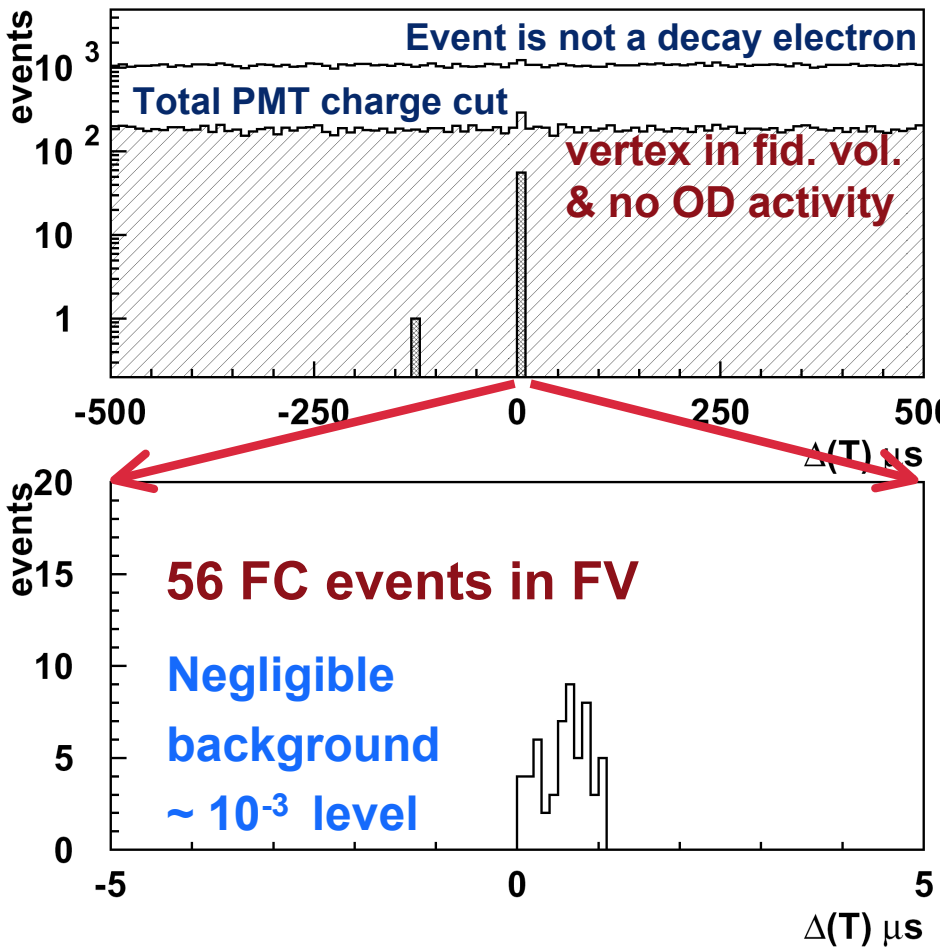
$$N_{SK}^{expected} = N_{KEK}^{measurement} \times R\ (Far/Near)$$

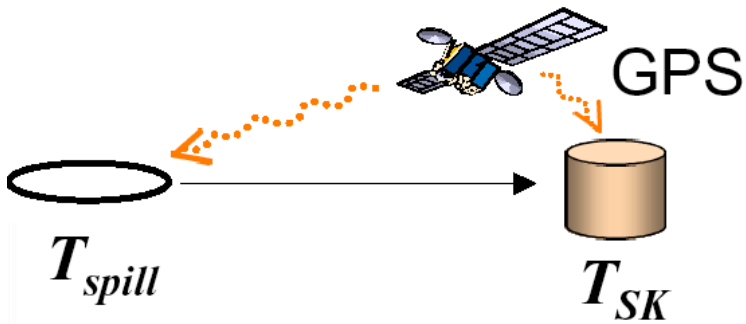
$$R = \frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)dE_\nu}{\int \Phi_{KEK}(E_\nu)\sigma(E_\nu)dE_\nu} \cdot \frac{N_{SK}^{Target\ mass}}{N_{KEK}^{Target\ mass}}$$



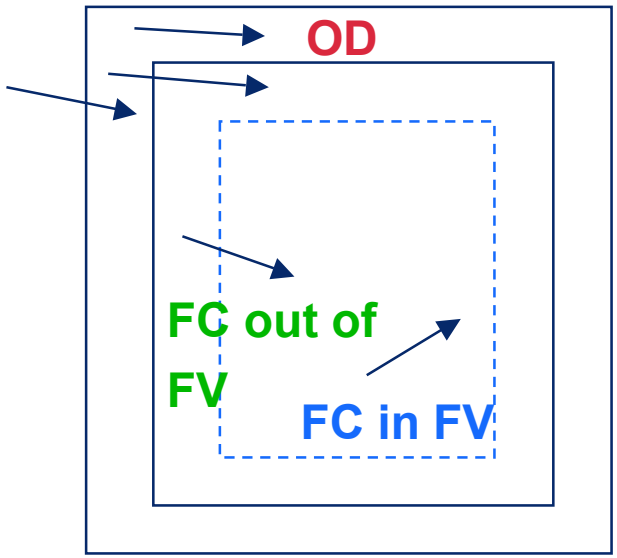
K2K Events Observed in SuperK

$$-0.2 \le \Delta T \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \le 1.3 \mu\,\mathrm{sec}$$

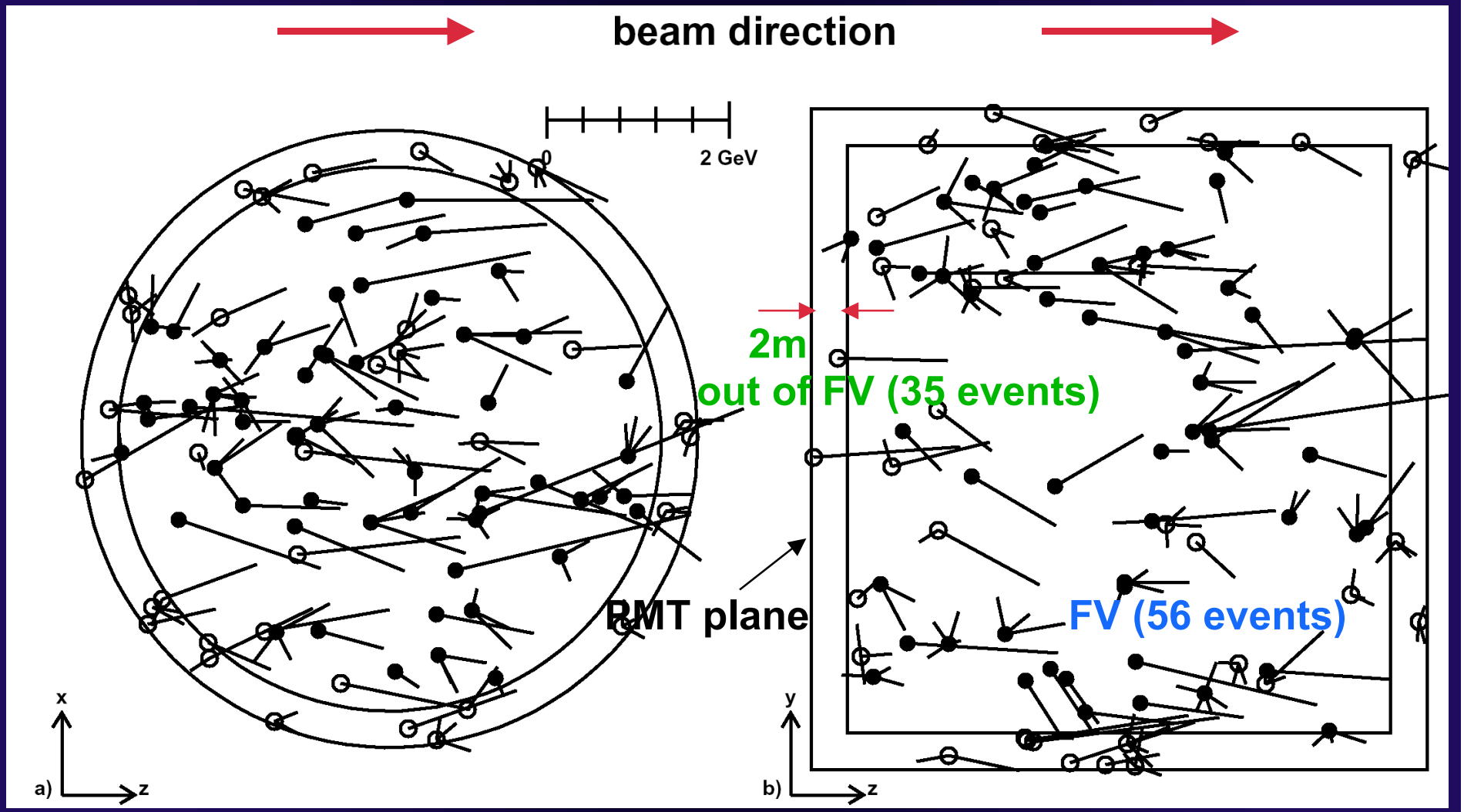




T_{Spill}: Abs. time of spill start
T_{SK}: Abs. time of SK event
TOF: 0.83ms (KEK to Kamioka)



Vertex Distribution of the K2K Events in SuperK



Oscillation analysis

1) Used data sets

1. Number of events

June ’99 - July ’01

FCFV events

(56 events)

2. Spectrum shape

Nov. ’99 - July ’01

1R□ events

(29 events)

2) Analysis methods

Maximum Likelihood method

$$L_{tot} = L_{norm}(f)\, L_{shape}(f)\, L_{syst}(f)$$

Normalization term

(No Oscillation Expected # of Events $N_{exp} = 80.1^{+6.2}_{-5.4}$)

Shape term (for 1R□)

Constraint term for systematic parameters. (error matrices)

Systematic Error Terms Considered for Oscillation Analysis

Systematic parameters

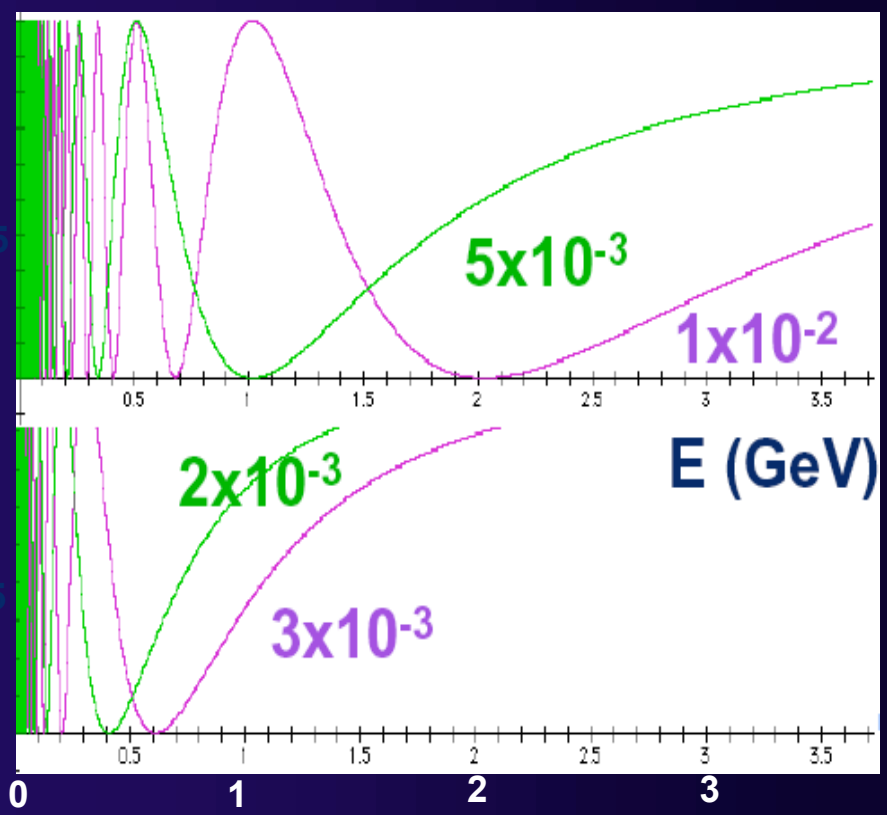
$$f = (f_{\Phi}, f_{nQE}, f_{\mathrm{F/N}}, f_{\varepsilon sk}, f_{Esk}, f_{n6}, f_{n11})$$

f_{ϕ} : Flux (8 energy bins)
f_{nQE} : QE/nQE ratio
$f_{F/N}$: Far/Near ratio
$f_{\varepsilon SK}$: SK reconstruction (Fid, PID, Nring)
f_{ESK} : SK energy scale
f_{n6} : Norm. for June 99
f_{n11} : Norm. Nov 99 ~ Jul 01

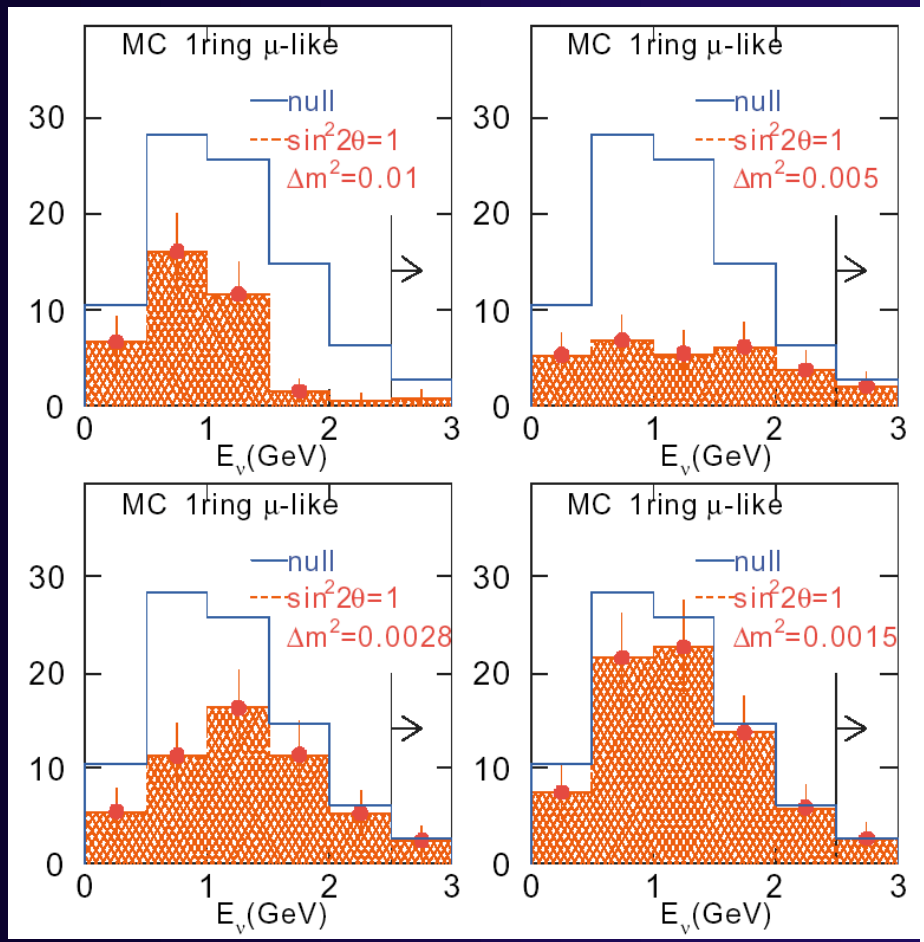
Neutrino Energy Spectrum at SuperK

$P_{\square\square\square>\square} = 1 - \sin^2 2\square \sin^2(1.27\square m^2 L/E)$

with $\sin^2 2\square = 1.0$, L=250km

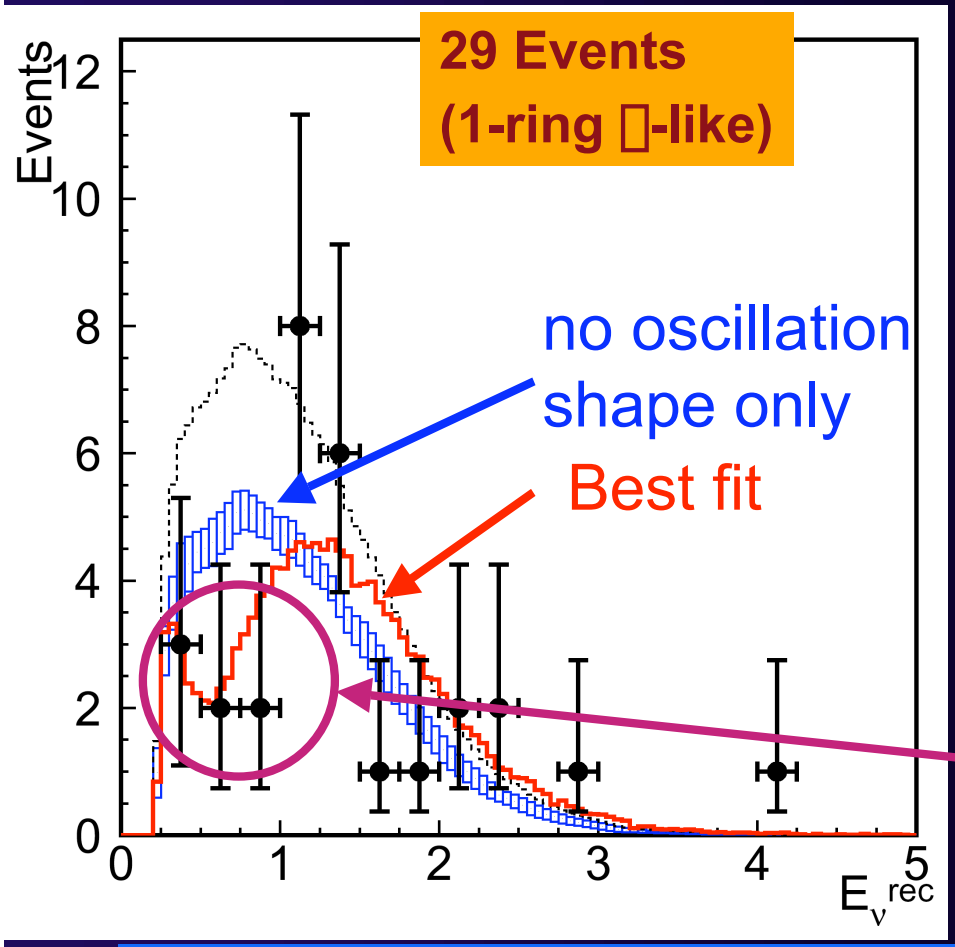


Reconstructed Neutrino Energy (MC)



Observed Energy Spectrum at SuperK and Fit Results

Reconstructed Neutrino Energy



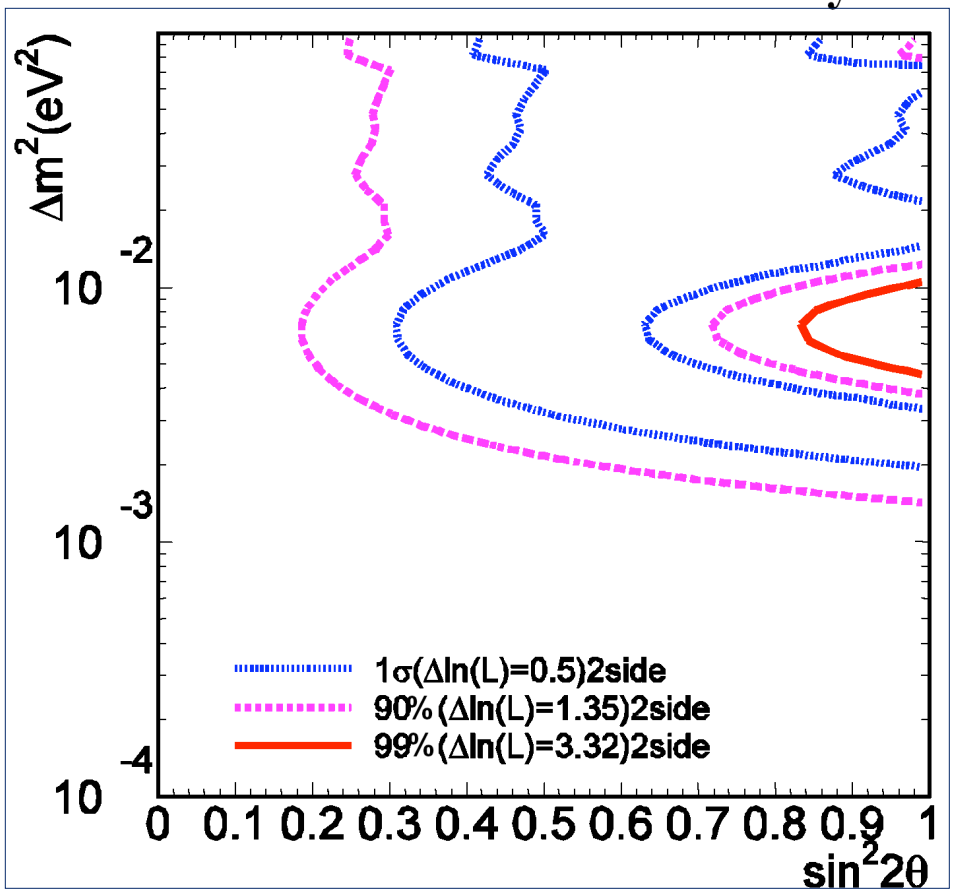
Best fit parameters
($\sin^2 2\theta$, Δm^2)
=(1.0 , 2.8x10^{-3} eV^2)

- **N_{SK}**
  Expected (w/ osc.) = **54**
  Observed = **56**
- **Shape**
  KS test **79%**

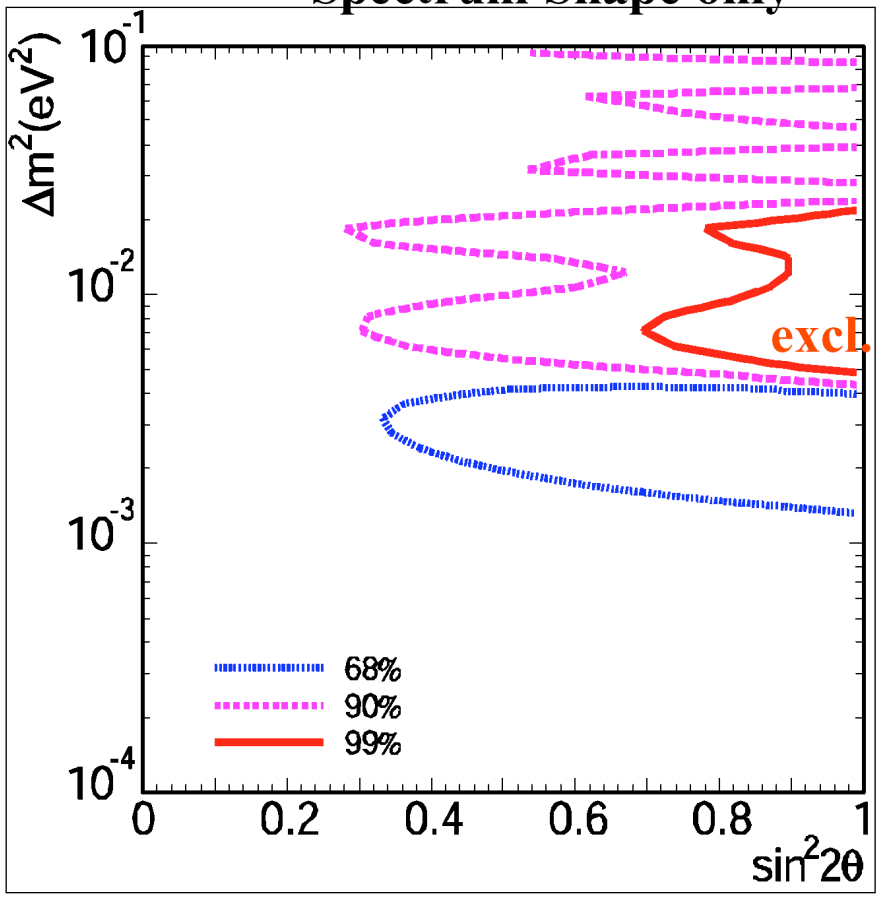
Could this be the first oscillatory pattern observed?

Allowed Regions

Total no. of Events only



Spectrum Shape only

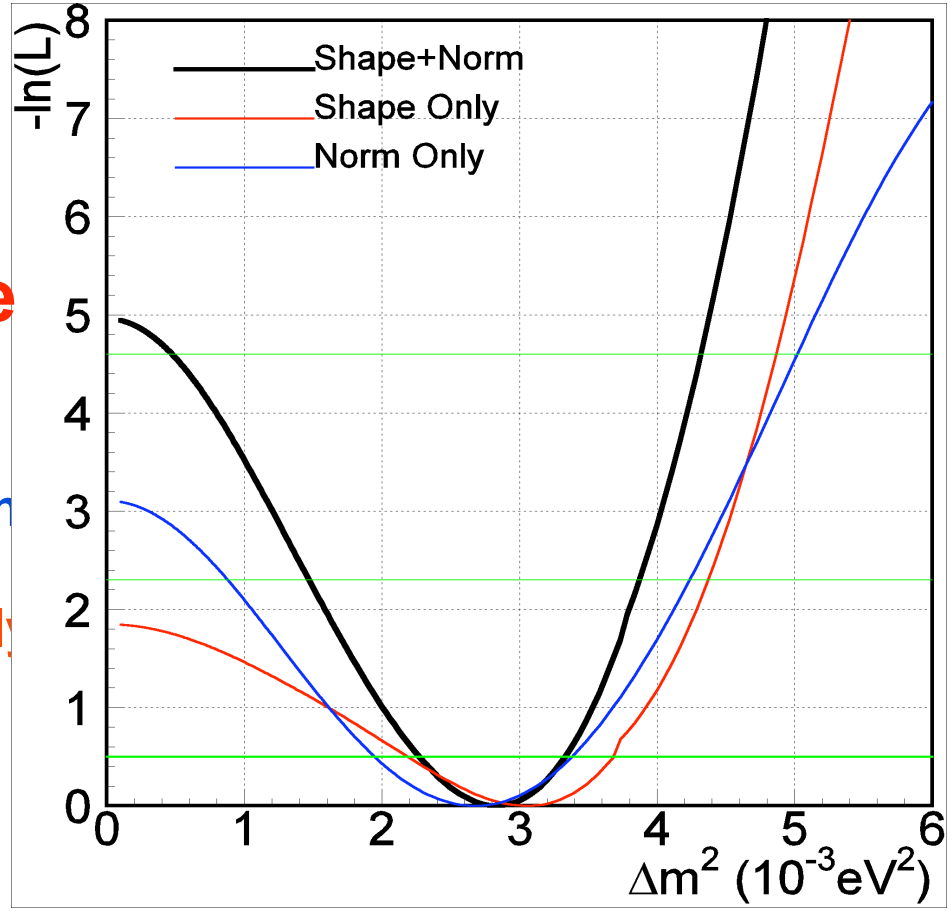


Allowed Δm^2

N_{SK} + Shape

Number of Events on

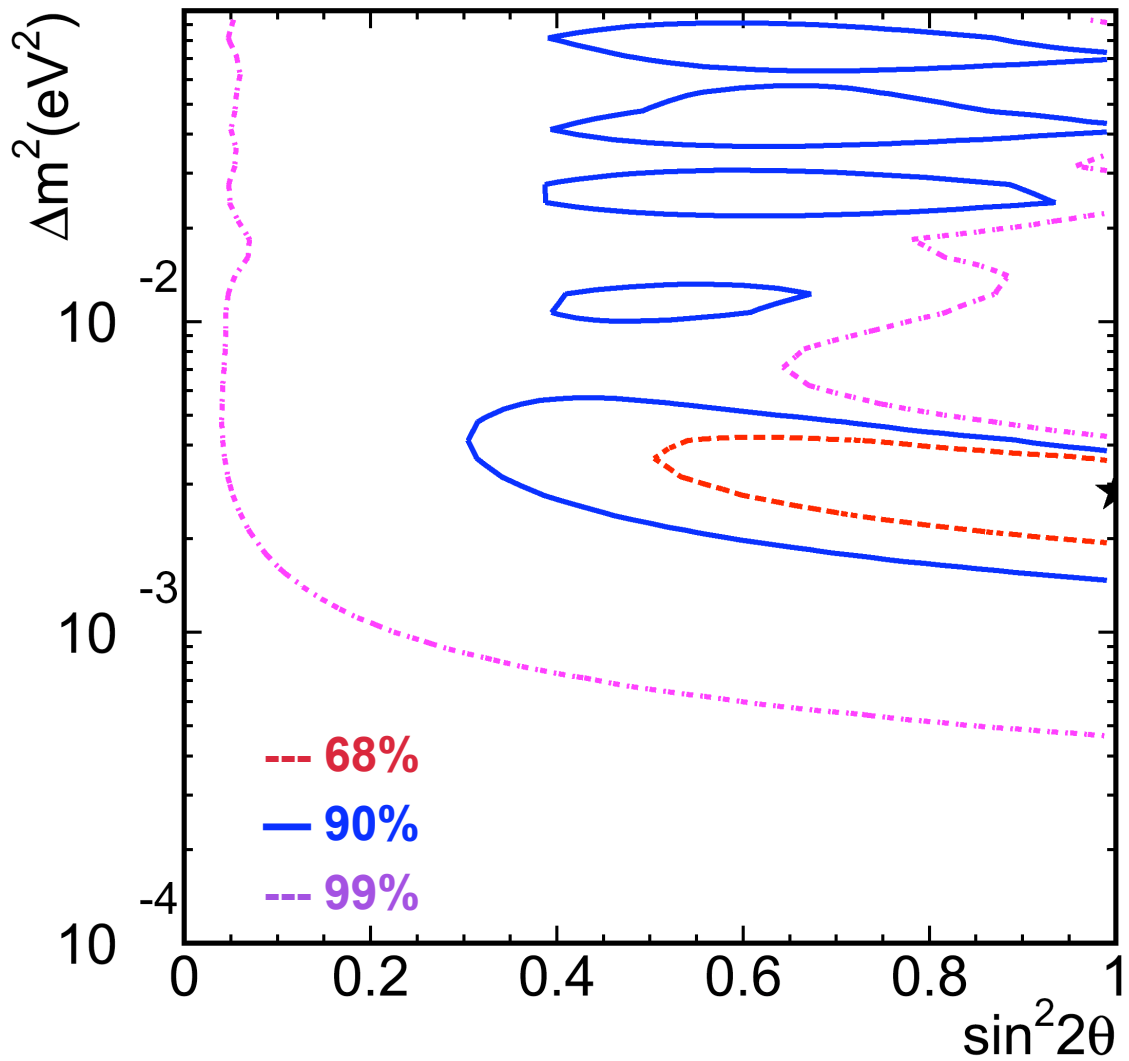
Spectrum Shape onl



N_{SK} and shape analysis indicate the same Δm^2 region for $\sin^2 2\theta=1$

K2K Allowed Region (2002)

Total number + Shape



Best fit parameters

($\sin^2 2\theta$, Δm^2)

(1.0 , 2.8×10^{-3} eV^2) K2K

(1.0 , 2.5×10^{-3} eV^2) SK

90%C.L. Δm^2 range @$\sin^2 2\theta$=1

$1.5 \sim 3.9 \times 10^{-3}$ eV^2 (K2K)

$1.6 \sim 3.9 \times 10^{-3}$ eV^2 (SK)

- Good agreement between K2K and SuperK

Null oscillation probability

Use □log(likelihood) from best fit point in the physical region

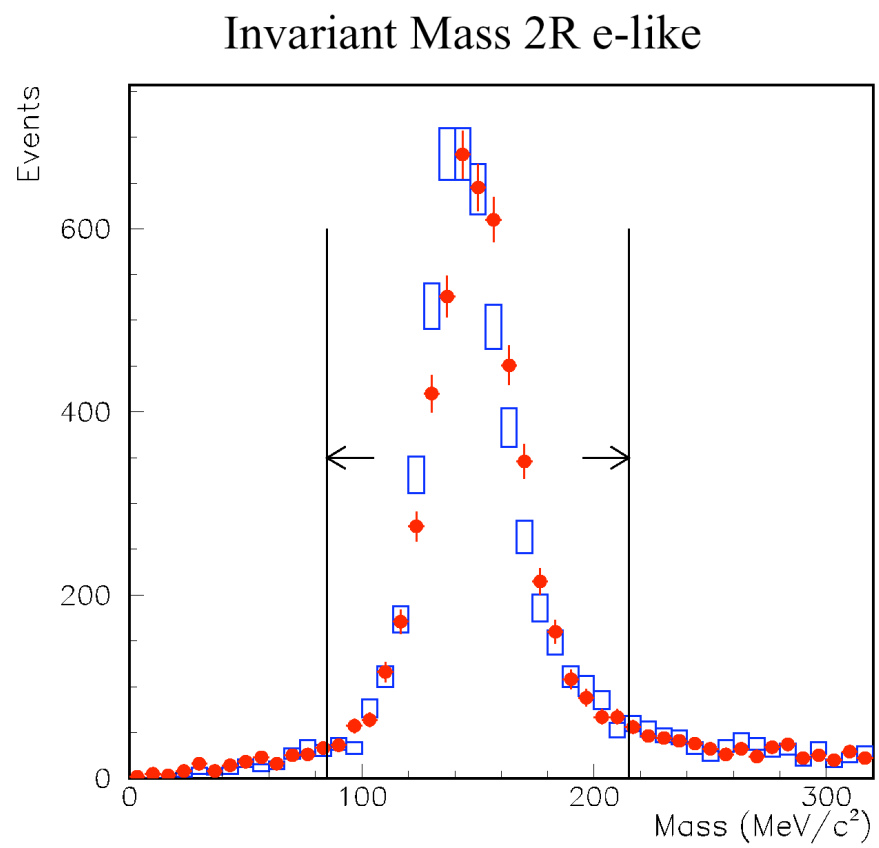
	method-1	method-2
N_{SK} only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK} + Shape	**0.7%**	**0.4%**

Probability of null oscillation is **less than 1%.**

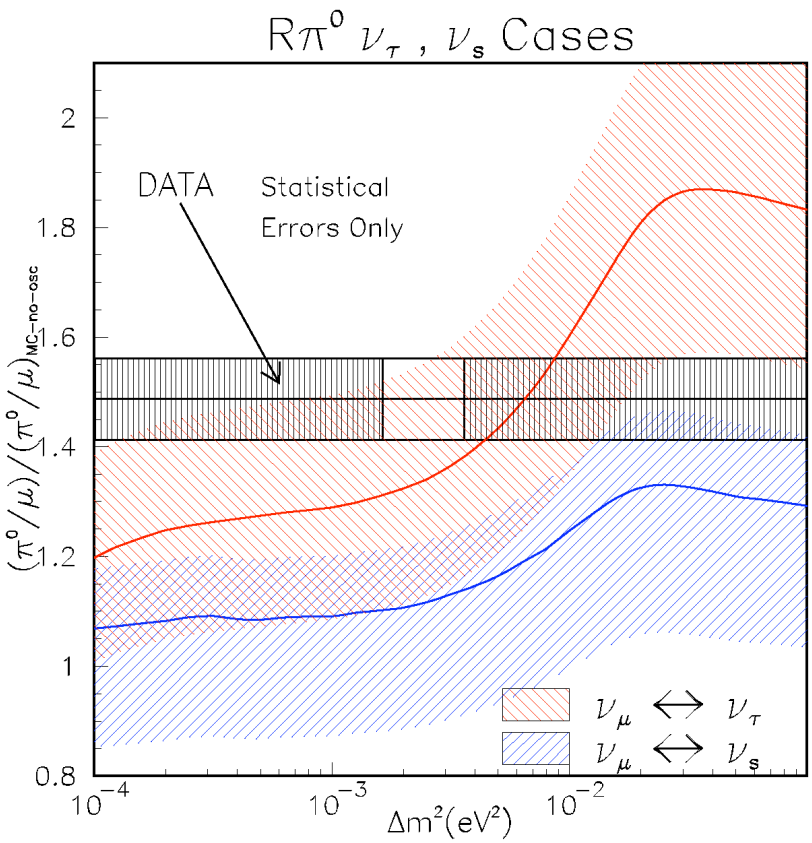
K2K π^0 Sample

Selection criteria similar to SK:

- two fully-contained rings
- Both identified as e-like
- $85MeV < M_{inv} < 215MeV$



NC π^0 Study for $\nu_\mu \leftrightarrow \nu_\tau$ vs $\nu_\mu \leftrightarrow \nu_s$ at SuperK



Recent results from K2K have made possible $\nu_\mu \leftrightarrow \nu_s$ studies using the NC π^0 sample.

- define double ratio:
  $R_{\pi^0} \equiv \frac{(\pi^0/\mu)_{data}}{(\pi^0/\mu)_{MC}}$ =1.00±0.02±0.09 (K2K)
- for each oscillation scenario, make predictions
- compare data with the predictions

$R_{\pi^0} = 1.49 \pm 0.08 \pm 0.22$

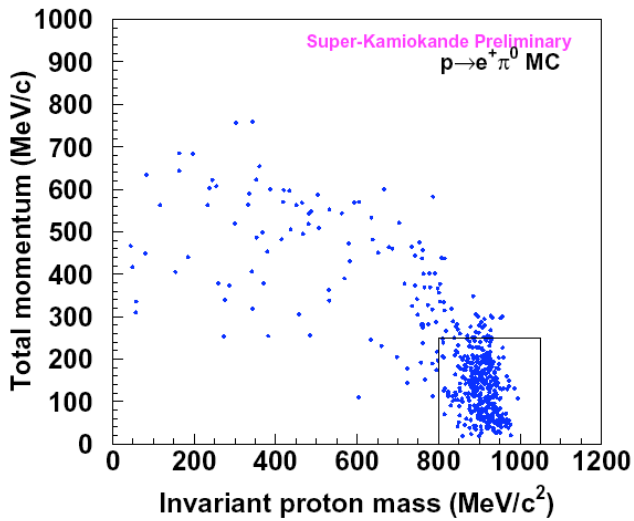
$\nu_\mu \leftrightarrow \nu_\tau$ prediction is 1.34

$\nu_\mu \leftrightarrow \nu_s$ prediction is 1.12

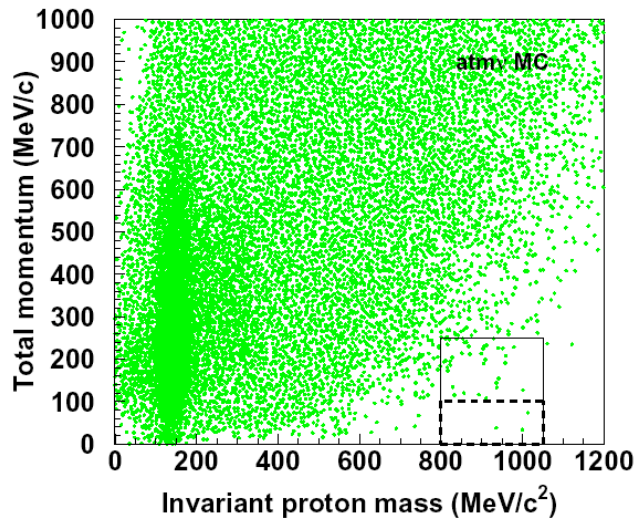
Data more consistent w/ $\nu_\mu \leftrightarrow \nu_\tau$

p → e⁺ π⁰ search in SuperK

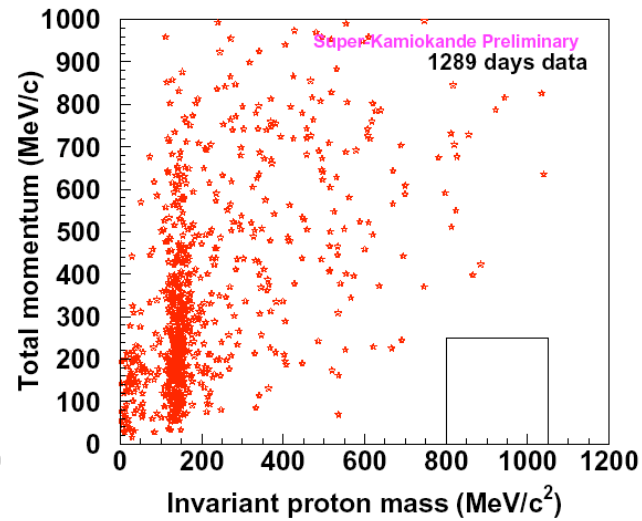
p → e⁺ π⁰ MC



atm ν BG MC



data



43% Signal efficiency

0.2 expected Background

0 candidate in Data

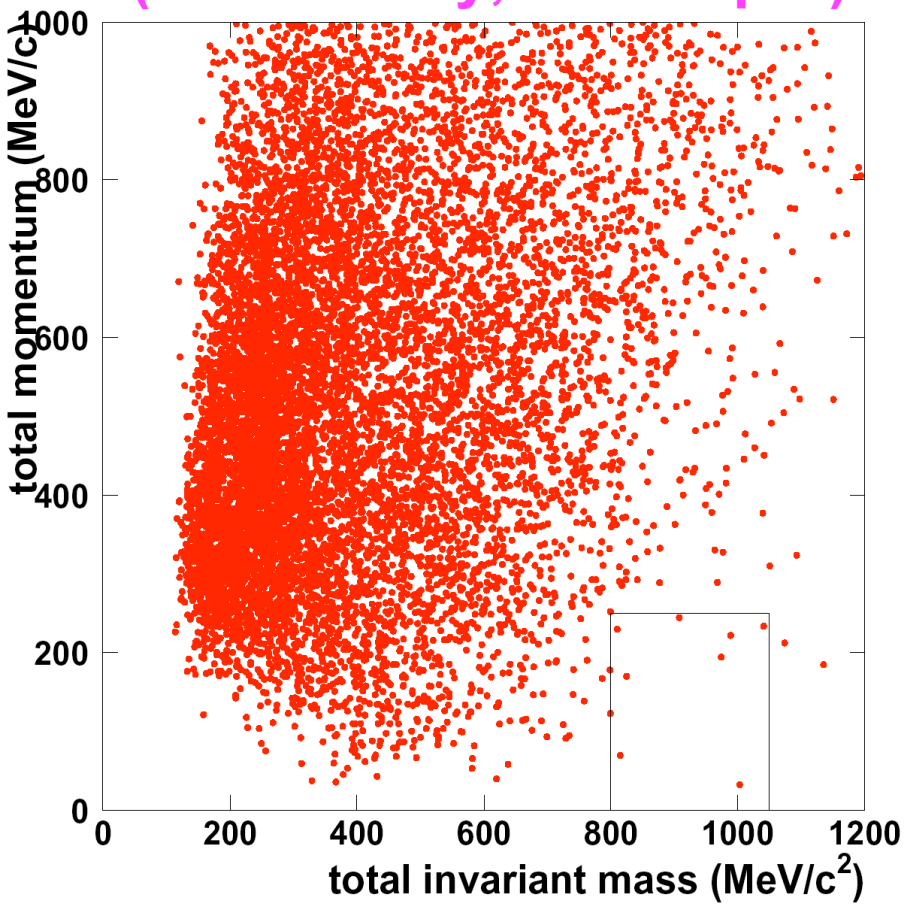
τ_B (p → e⁺π⁰) > 5.0 x 10^{33} yrs (1289 days Limit @90% C.L.)

5.7 x 10^{33} yrs (1489 days SuperK-I Limit @90% C.L.)

Validation of Atmospheric Neutrino Background MC

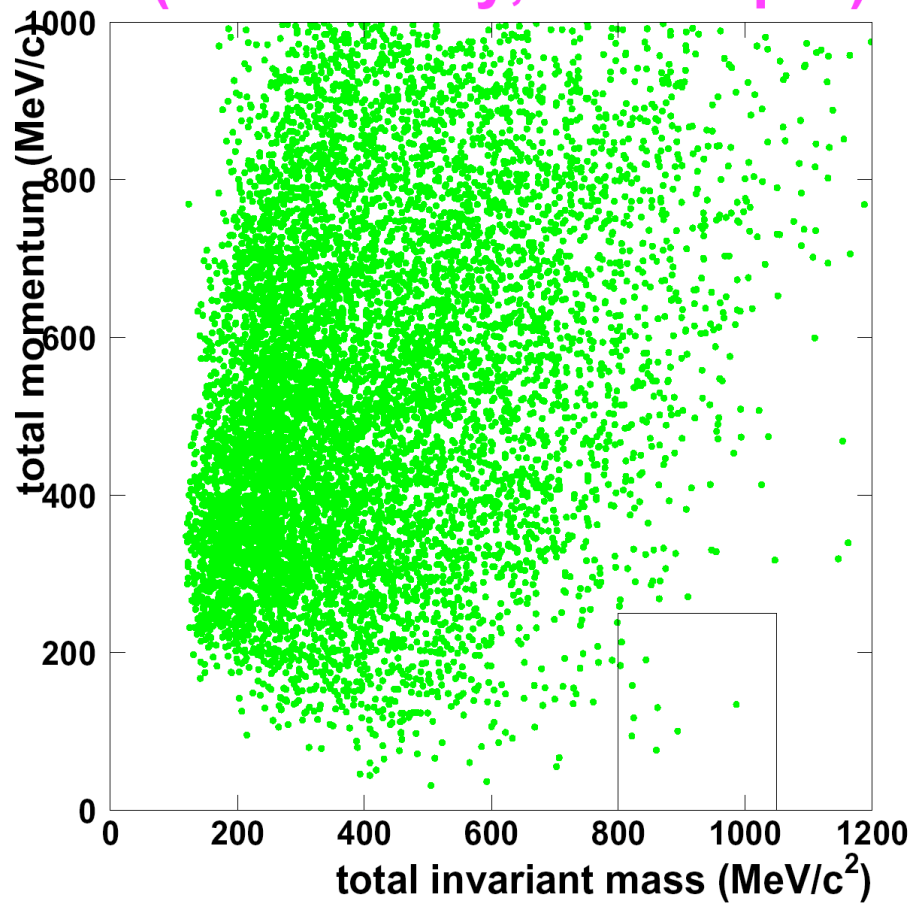
1KT DATA N ^{0} N' 1KT MC

(Preliminary, ~3x10^{19} pot)



(~3Mtyr atm ν_μ equiv.)

(Preliminary, ~3x10^{19} pot)

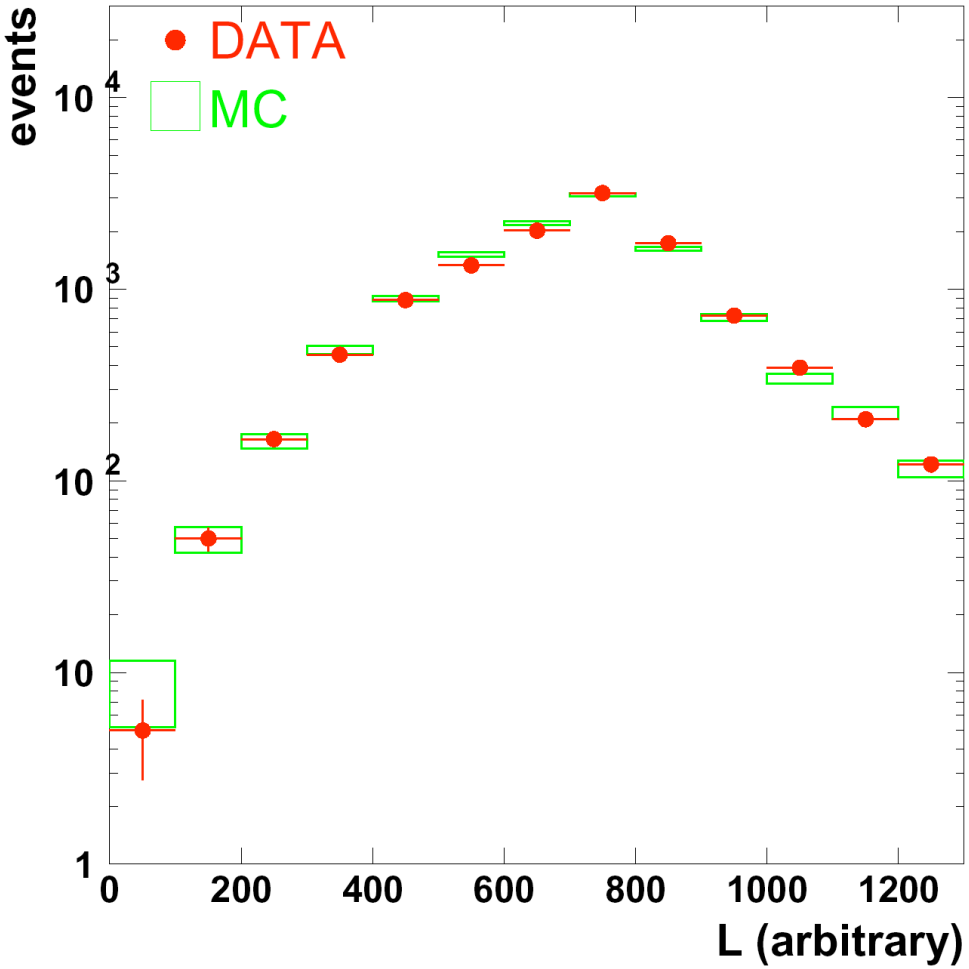


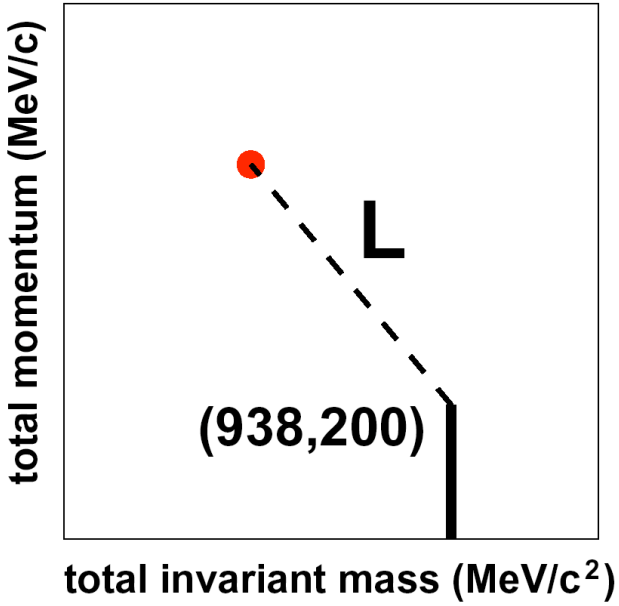
(~3Mtyr atm ν_μ equiv.)

Distance from the PDK Signal Box

distance "L" in mass vs. momentum plot

(1KT preliminary, ~3x10^{19}pot)

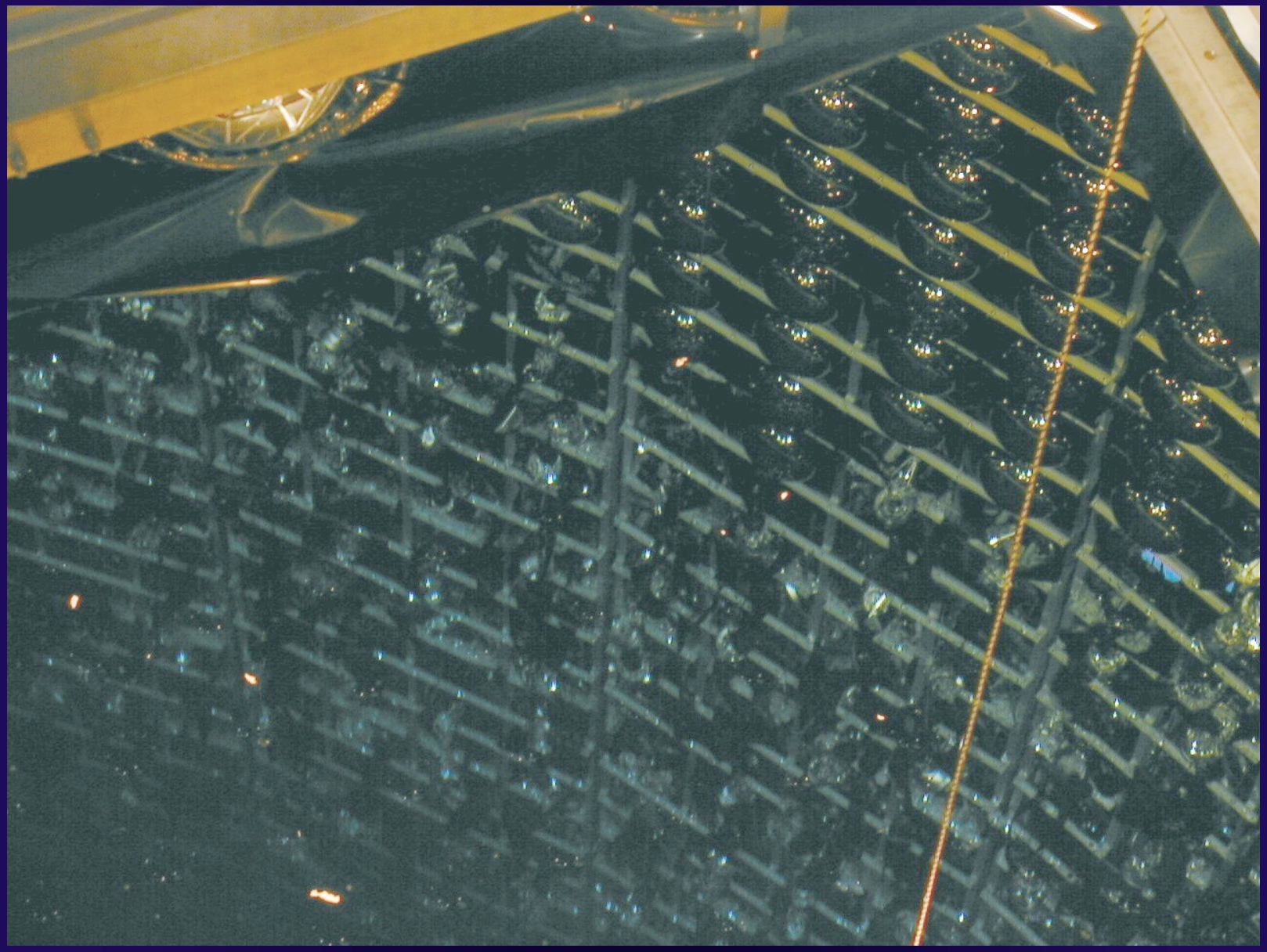




November 2001 SuperK Accident

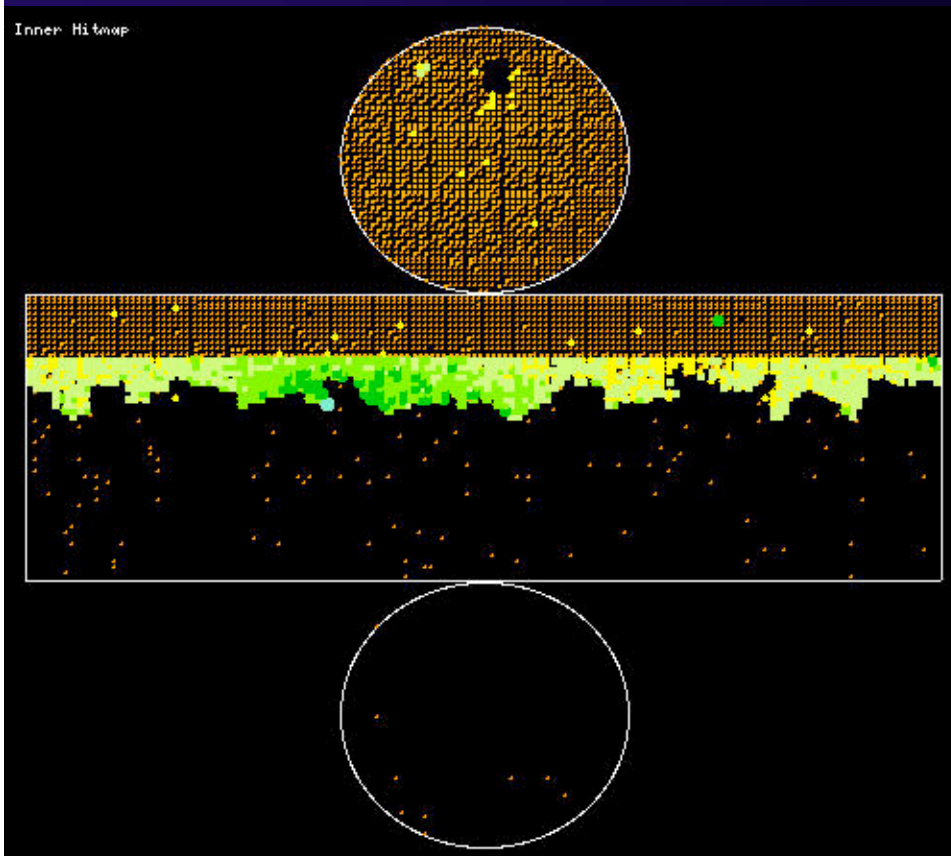
- April 1996 - SuperK began data taking
- July 2001 - Began draining SuperK tank for upgrade/repair
  - replaced about 250 inner detector 20” tubes and 280 8” outer detector tubes
- Nov 12, 2001 - Apparent chain reaction of imploding PMTs extensively damaged SuperK while the tank was being refilled
  - Water level was about 7 meters from the top
  - The chain reaction was most likely initiated by a single PMT implosion

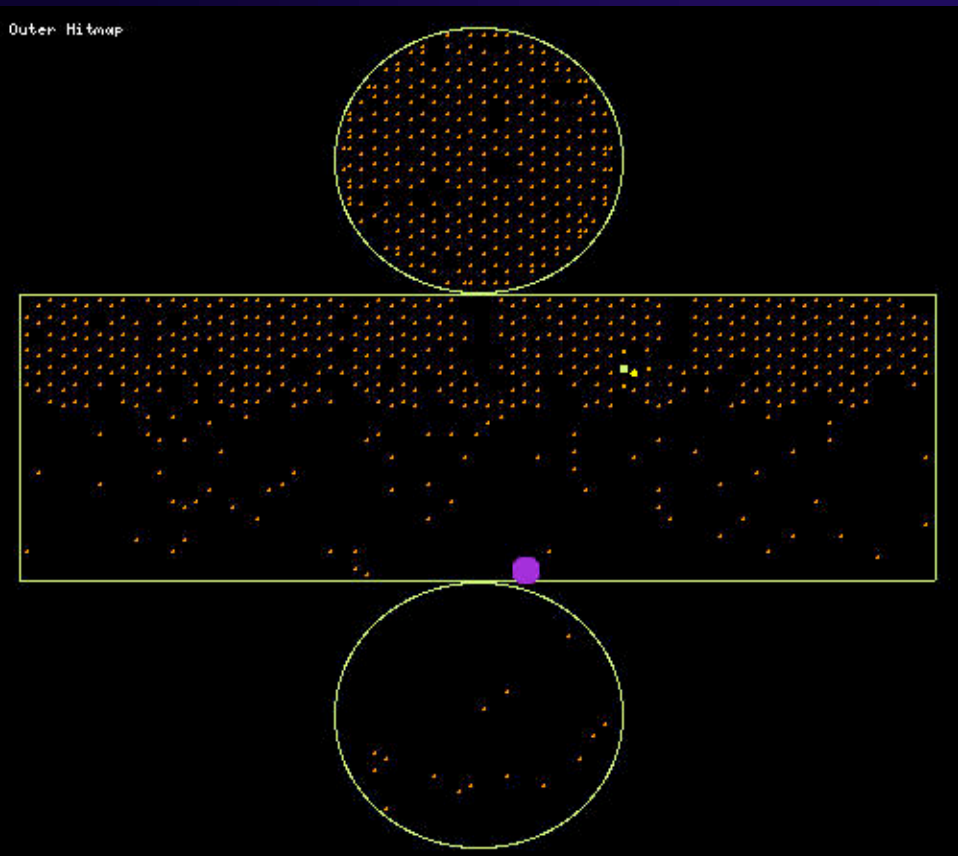
Damaged SuperK ID



November 2001 SuperK Accident
Summary of the Damage

ID **OD**

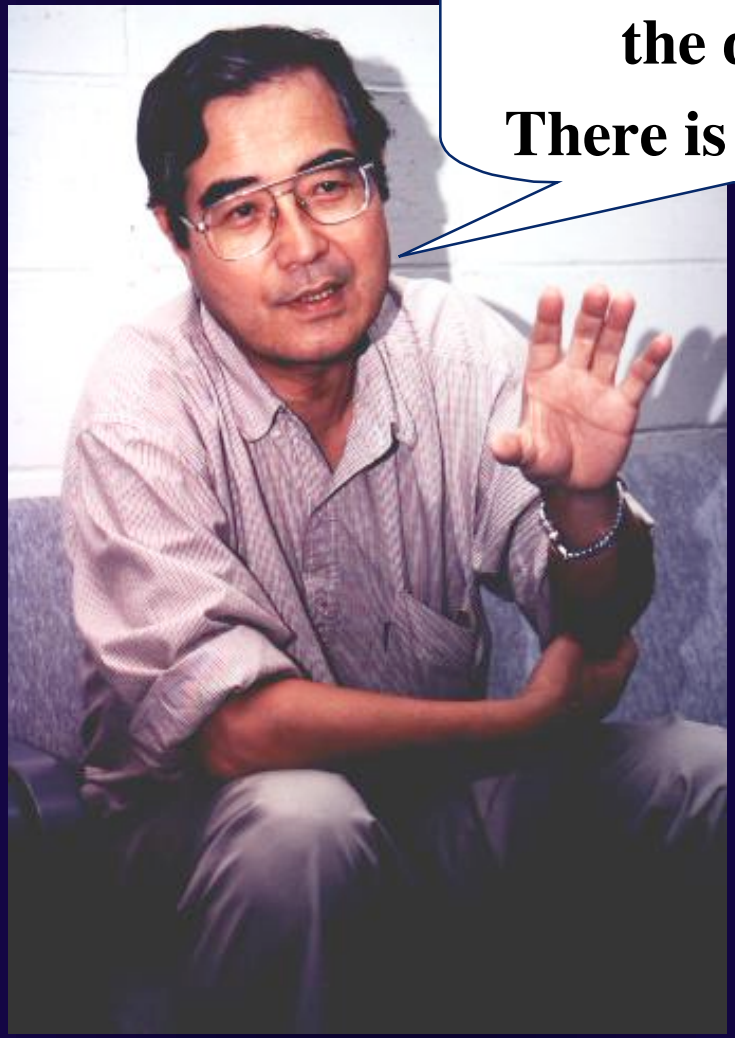




6777 (out of 11146 20” tubes)

1149 (out of 1885 8” tubes)

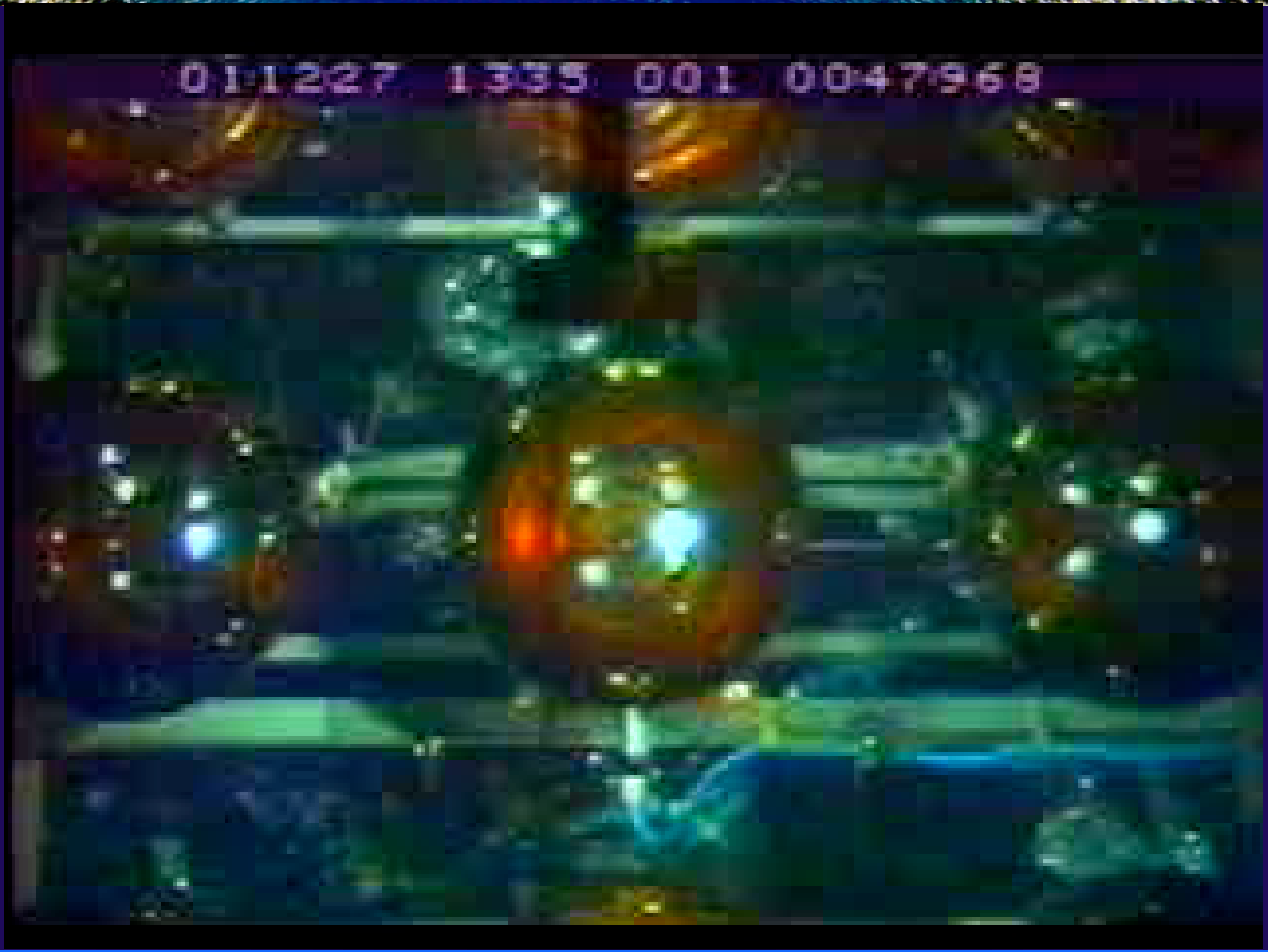
Y. Totsuka soon after the accident…



We will rebuild
the detector.
There is no question!

SuperK Accident Simulation I

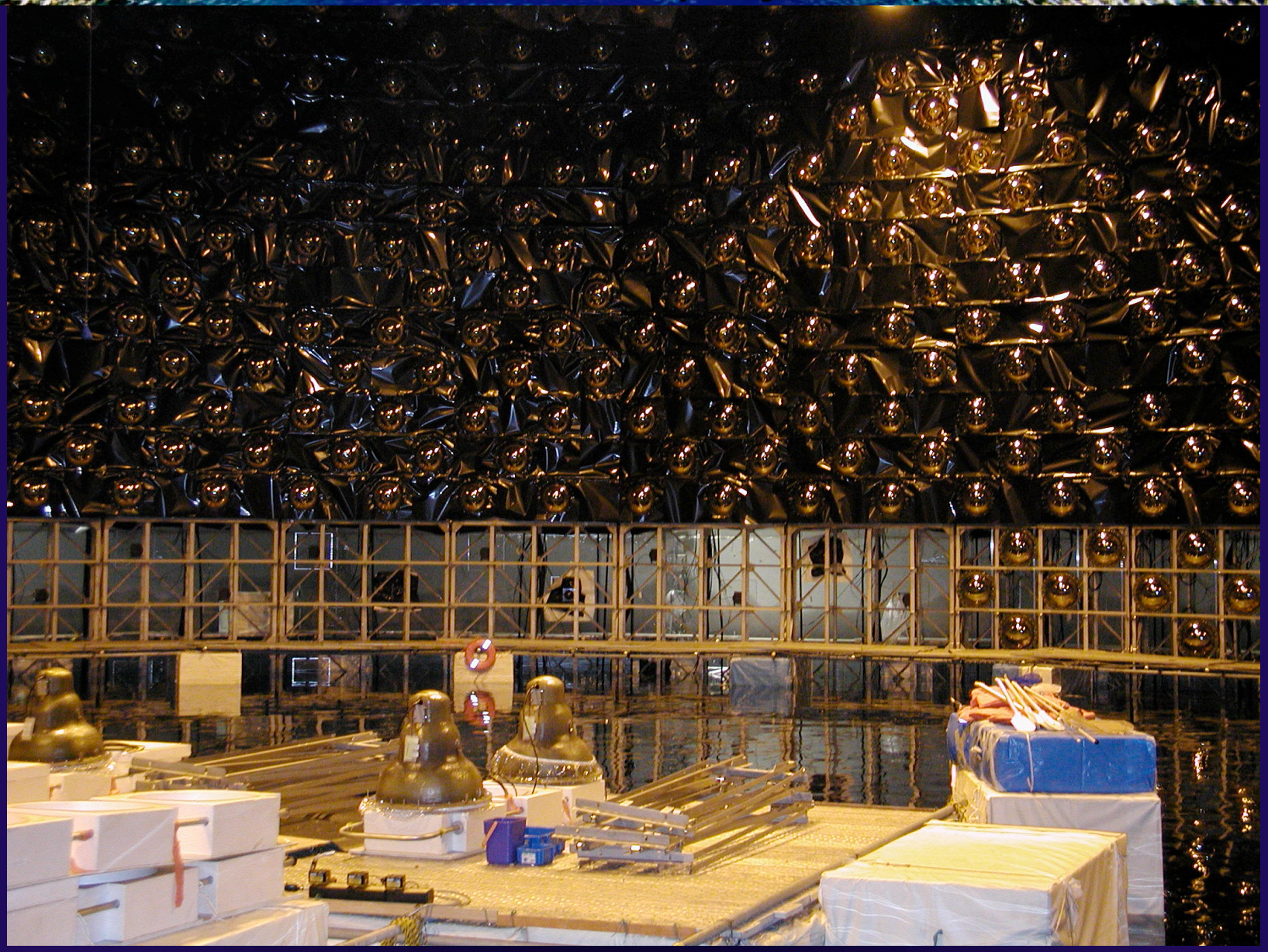
SuperK Accident Simulation II



Protective PMT Cover Test I

Protective PMT Cover Test I

Super-Kamiokande-II Construction (July 2002)

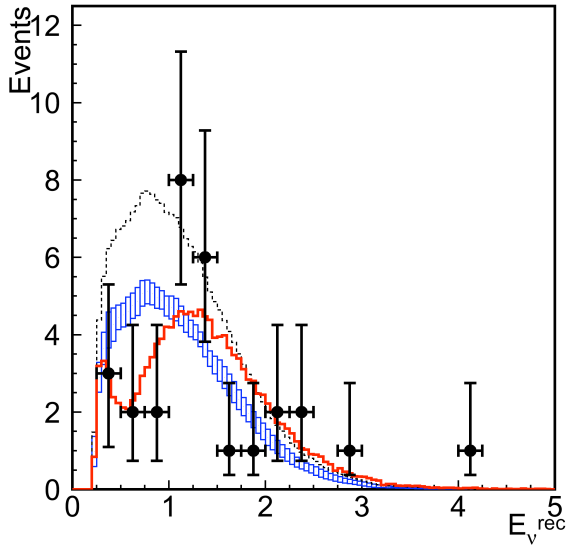


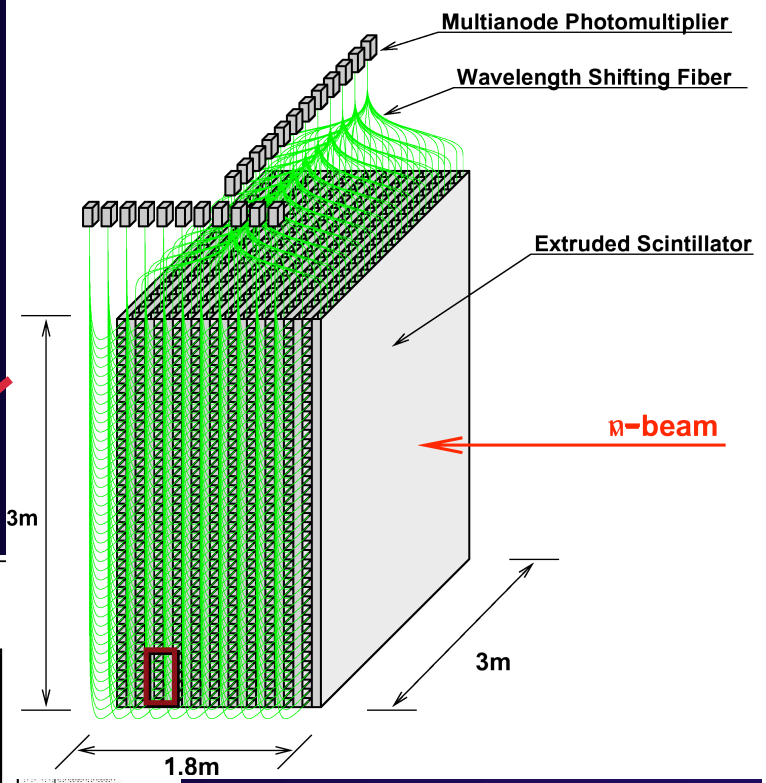
Future (Tentative) Plans for SuperK and K2K

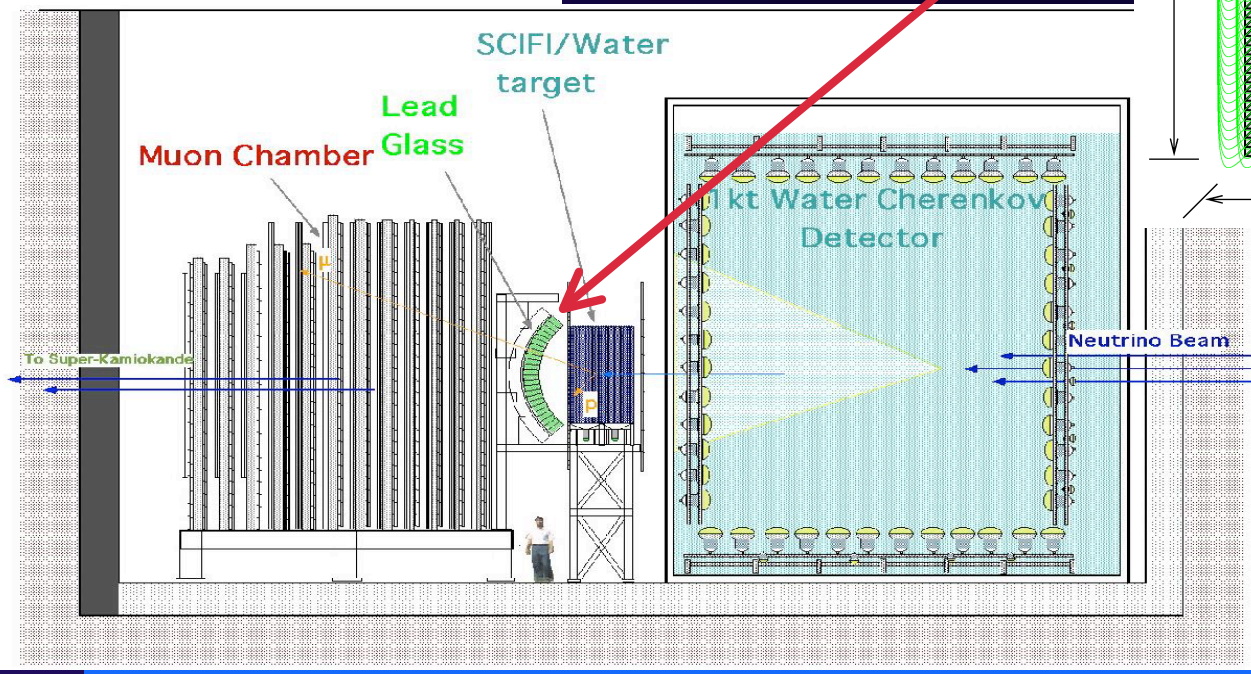
- End of 2002: Completed SuperK Rebuild
  - 20% ID photo-cathode coverage (1/2 of the original density) and full original OD coverage
- Jan. 2003: Resume K2K data taking
  - Accumulate 10^{20} POT by Mar. 2005
  - Both SuperK and K2K are taking data now
- Summer 2003: Upgrade K2K near detector
  - Add fine-grained scintillater (Sci-bar) detector in place of the lead-glass calorimeter (already removed)

    Measure low energy (<1GeV) neutrino spectrum better
- ~2006: Re-instrument SuperK ID to full 40% coverage
- ~2007: Begin JHF ---> Kamioka neutrino experiment
  - Measure $\sin^2\theta_{13}$ (U_{e3})

Scibar Detector







JHF Neutrino Experiment
(w/ off-axis beam)

Plan to start in 2007

1st experimental proposal w/ a specific Goal of:

observing $\nu_\mu \to \nu_e$ appearance

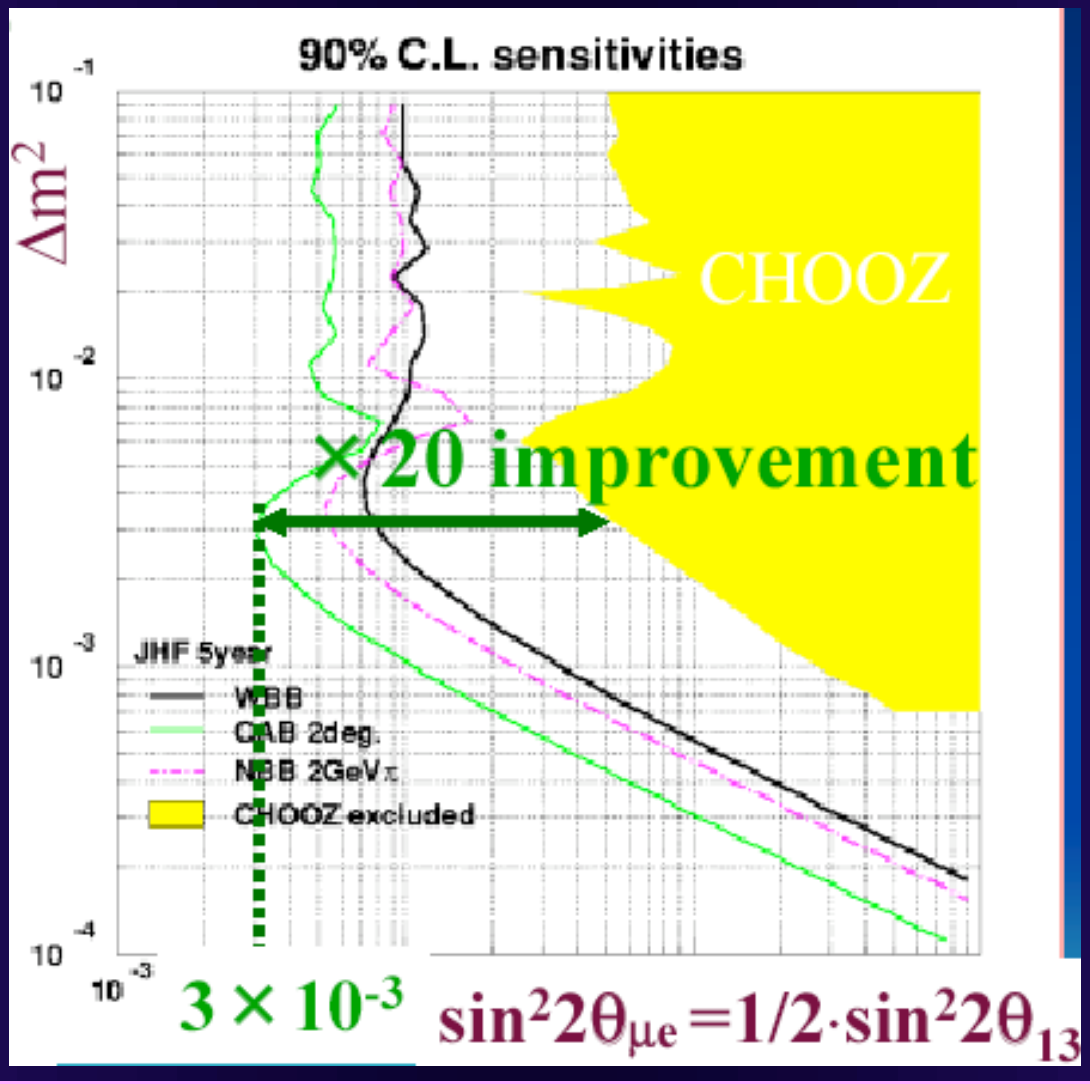
→ measure $\sin\theta_{13}$

ventional ν beam)

Kamiokande)

Phase-I × 200

JHFnu Sensitivity



$\sin^2 2\theta_{13} < 0.006$ (90% C.L.)

Conclusion

- K2K Beam intensity at the design level
  - June 1999 - July 2001 data: ~5 x 10^{19} POT
    - Goal: accumulate 10^{20} POT (~until Mar. 2005)
- Oscillation analysis performed with full error analysis
    - null oscillation probability < 1%
    - results consistent with the SuperK atm nu oscillation analysis results
- Other cross-section measurements are underway
    - π^0/π results to be published soon
- Preliminary results on background study for proton decays
    - Paper being prepared

continue: Conclusion

- First successful long-baseline neutrino oscillation experiment w/ a baseline O (100km)
  - leads to rich neutrino physics programs of future long-baseline experiments: MINOS, CNGS, JHF--> SuperK, superbeams and neutrino factories...
- Neutrino Oscillation: only evidence for physics beyond SM

(MNS) □ (CKM)

- GUT? Proton decay? CPV in Lepton sector? Lepto-genesis?

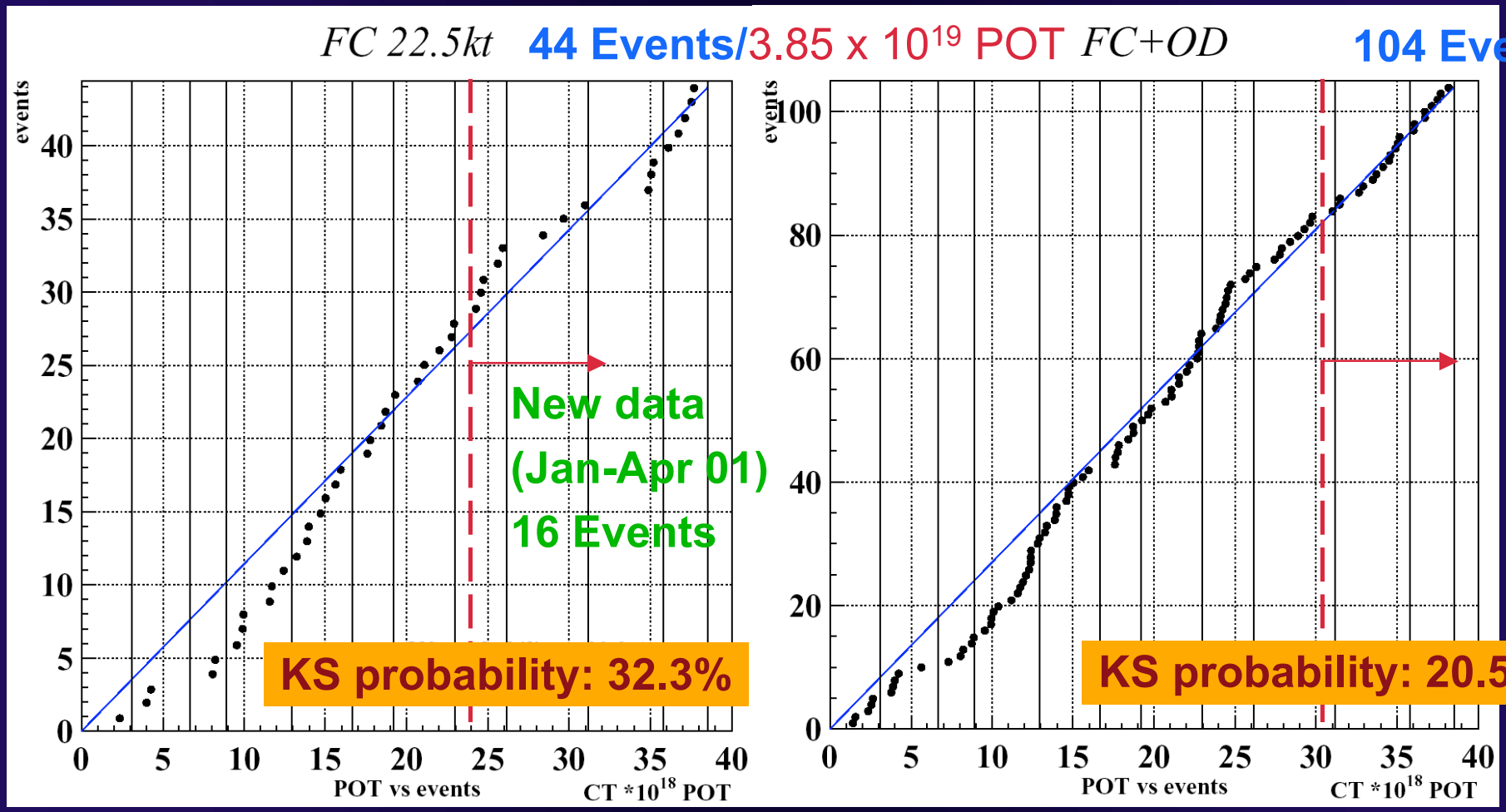
  □ exciting times are ahead of us

The End

Observed # of K2K Events vs. POT in SuperK

Events within FV

All Events



of Observed Events vs. the Expected at SuperK

June 1999 - April 2001

FC Events in FV

	Obs.	No Osci. (1kton)	$\Delta m^2(\times 10^{-3} eV^2)$ 3	5	7
			($\sin^2 2\theta=1$)		
FC 22.5kt	44	$63.9^{+6.1}_{-6.6}$	41.5	27.4	23.1
1-ring	26	38.4 ± 5.5	22.3	14.1	13.1
μ-like	24	34.9 ± 5.5	19.3	11.6	10.7
e-like	2	3.5 ± 1.4	2.9	2.5	2.4
multi ring	18	25.5 ± 4.3	19.3	13.3	10.0

of Observed Events vs. the Expected at SuperK

1999/06-2001/04

FC Events in FV

	Obs.	No Osci. (1kton)	$\Delta m^2(\times 10^{-3} eV^2)$ 3	5	7
			($\sin^2 2\theta=1$)		
FC 22.5kt	44	$63.9^{+6.1}_{-6.6}$	41.5	27.4	23.1
	new (16	26)			
1-ring	26	38.4 ± 5.5	22.3	14.1	13.1
μ-like	24	34.9 ± 5.5	19.3	11.6	10.7
e-like	2	3.5 ± 1.4	2.9	2.5	2.4
multi ring	18	25.5 ± 4.3	19.3	13.3	10.0

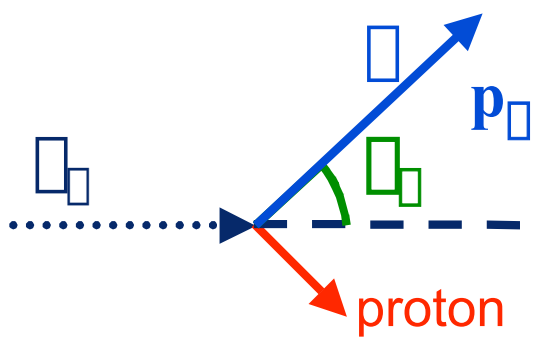
==> Null Oscillation probability: less than 3%

Reconstruction of neutrino energy at SK

Use **single-ring μ-like FCFV** (1Rμ) events

Assuming **QE interaction** and **reconstruct E_ν**

(**~50%** of K2K 1Rμ events are **CCQE**)



$$E_\nu^{rec} = \frac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + P_\mu \cos\theta_\mu}$$

E_μ : muon energy

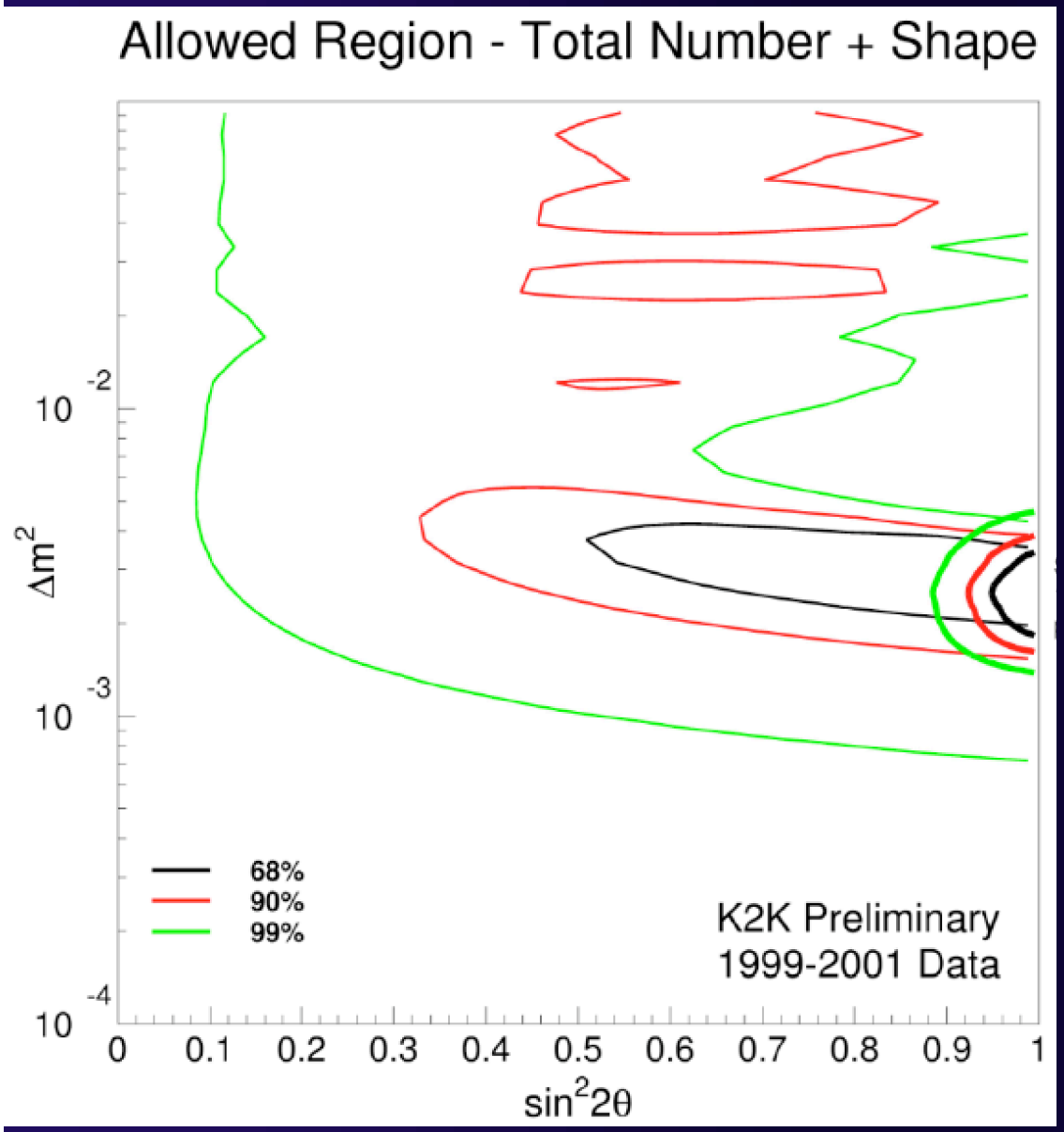
p_μ : muon momentum

θ_μ : muon angle

Systematic Errors in SuperK Expected

- Systematic Errors (1kton and SuperK)
  - water target, similar detector common sys. errors
    - some sys. errors such as x-section errors cancels out
  - Dominant sys. errors
    1) Far-near ratio: ~7%
    2) 1kton fiducial volume: ~4%

K2K Allowed Region (2002)



Best fit parameters

($\sin^2 2\theta$, Δm^2)

(1.0 , 2.8×10^{-3} eV^2) K2K

(1.0 , 2.5×10^{-3} eV^2) SK

90%C.L. Δm^2 range

@$\sin^2 2\theta$=1

$1.5 \sim 3.9 \times 10^{-3}$ eV^2 (K2K)

$1.6 \sim 3.9 \times 10^{-3}$ eV^2 (SK)

- Good agreement between K2K and SuperK